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METHODOLOGY FOR RISK ANALYSIS OF RAILWAY GROUND HAZARDS

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ABSTRACT

Railway ground hazards (RGH) are broadly defined as landslides, subsidence, hydraulic erosion and snow and ice hazard events that have the potential to directly or indirectly result in track failure. In Canada, they represent a significant safety and operating risk to railways and warrant the development of a systematic risk management methodology. The thesis completes the preliminary analysis, the essential second step in the six step process towards risk management (CSA, 1997) and organizes the information to facilitate the third step risk estimation.

The thesis includes development and use of a RGH classification system to analyze the loss records for CN Western Canada between 1992 and 2002 to obtain details of the historical frequency and severity of loss stemming from RGH in Canada.

A methodology is developed to identify and characterize the RGH risk scenarios. It involves description of the railway ground hazard risk scenario and its relevance to the risk algorithm (probability x severity); the methods to characterize each of the factors that make up the algorithm, namely, the railway ground hazard scenario probability, track vulnerability, service disruption vulnerability, derailment vulnerability; and finally the consequence severities.

The RGH risk scenario characterization methodology is then applied to systematically characterize the identified RGH in CN Western Canada. Forty railway ground hazard scenarios are identified from the database describing the majority of the 2900 ground hazards identified. The initial listing of the railway ground hazard scenarios are grouped by the initiating ground hazard event into rock landslides, debris landslides earth landslides, subsidence, overland / through flow erosion and channelized flow erosion. Chapters 6 through 11 characterize the identified railway ground hazard scenarios in CN

Western Canada within these groups, utilizing the methodology developed in Chapter 4. In each chapter similar conditions and processes, timing, rates and lag times, preparatory and trigger causal factors and track, service disruption and derailment vulnerability, common to the group, are identified and described. The results of these chapters populate the initial risk library necessary to move to the next steps in the risk management process. Suggestions on specific initiatives to progress to these next steps, are provided.

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Chapter 1 Introduction

Ground hazards, broadly categorized as either, geotechnical or snow and ice related, are known to represent a significant exposure to accidental losses or risk to Canadian railways. Linear facilities are inherently more exposed to a wider variety and higher frequency of ground hazards than single site facilities. Furthermore, in comparison to other linear features, railways have higher exposure to ground hazards because of their grade and curvature limitations which have resulted in higher cut and fill sections. Railways traversing North America cross a wide variety of physiogrphic regions and relief. Canadian railways, in particular, have an incrementally higher frequency of loss from ground hazards in comparison to those in the United States or Mexico due to:

- A greater diversity of soil and rock conditions,
- More extensive and deeper ground freezing conditions and related peat terrain,
- More active geomorphologic processes associated with the relative youth of the rivers since glaciation, and
- Climate extremes in both temperature and precipitation.

Railway ground hazard incidents may occur in isolated, high relief locations often adjacent to a body of water (river or lake). This setting contributes to incrementally higher severity, on average, in terms of injury or fatality, property loss, track outages, recovery time and costs, environmental impacts and liability exposures. To illustrate this effect, a review of CN's accident and loss records, presented in Chapter 3 of this Thesis, reveals that on CN track, the average direct cost per railway ground hazard train accident between 1992 and 2002 is $350,000 which is five times greater than the next highest, train accident cause, namely rail defects.

It follows that as the frequency and severity stemming from railway ground hazards in Western Canada is incrementally higher then the rest of Canada, the risk is incrementally higher as well. As much of the terrain traversed by Canadian railways is sparsely populated, and resources available to mitigate associated hazards have always been limited, it is not possible to simply eliminate this risk but, instead, a systematic and coordinated change in approach can have a dramatic effect in reducing the losses attributable to railway ground hazards. As an example, in 1972, faced with an unacceptable 35-year record of 24 deaths and 185 injuries resulting primarily from rock falls in BC, Canadian National Railways initiated aggressive corrective action. The new approach was a fundamental shift from reactive to proactive hazard management. The approach involved the following key components:

- To increase safety against rock falls by a consistent long-term improvement program with carefully selected priorities.
- Establish and maintain an inventory of individual locations where rock fall hazards exist.
- An appropriate amount of capital budget was allocated for "planned" work to reduce the risk at identified high hazard sites.
- Mitigation programs were to be planned years in advance, using primarily subjective prioritization by experienced professionals.
- A philosophy was developed to govern the choices of treatment methods based on their effectiveness for stabilization (reduces frequency), protection (reduces severity) or provide warning (reduces severity).

As a result, of this fundamental change in approach, the number of rock fall related deaths or injuries dropped dramatically in the past 30 years, and as shown in Chapter 3, rock fall hazards now rank fourth in annual direct costs behind other ground hazards. Although this approach continues today, it primarily focuses on rock fall hazards and relies on the experience and subjective assessment of experienced geotechnical engineers for hazard management.

In 1996, CN undertook an independent review of its management of railway ground hazards (BGC, 1996). The review found that CN was overall at the industry standard-of-practice, and was in some areas at the state-of-the-art in their management of railway ground hazards due mostly to their development of the CN rockfall hazard and risk assessment (CNRHRA) system (Abbott et al, 1998 a, b). The review went on to say that there was a growing international trend towards formal risk management and that CN would be well advised to move in this direction in the area of ground hazards.

Over the last decade there has been increased focus on the risks these hazards pose to railway operations. It came from rising public and employee awareness, greater regulatory scrutiny, increased inter-railway competition, deregulation, reduction of available resources, privatization, and increased traffic. It came to the forefront in March of 1997 when CN suffered a fatal freight train derailment near Lytton B.C. in which the two train crewmembers perished and the main line was out of service for 1.5 weeks. The derailment was caused by an embankment failure triggered by an intense snowmelt event at a location not known to be problematic. Following intense internal and external scrutiny, CN made the corporate decision to adopt a risk management approach to manage railway ground hazards.

In 1999 CN produced an internal document entitled Canadian National Railway Grade and Slope Stabilization: Engineering and Management Protocol (Keegan and Ruel, 1999) hereafter referred to as the Protocol. For many years, CN has carried out regular proactive programs of grade and slope stabilization. The intention of the Protocol was to bring together and refine the various elements of these programs and describe a systematic process comprising:

1. identifying natural hazards,
2. documenting relevant information relating to natural hazards,
3. monitoring the status of identified natural hazard locations,
4. developing action plans to reduce the potential for grade and slope failure,
5. implementing programs of grade and slope stabilization, and
6. following up on stabilization programs to evaluate method effectiveness.

The grade and slope stabilization process described in the Protocol is depicted in Figure 1-1. The Protocol documented CN's current systematic process for the management of railway ground hazards using hazard management procedures. More importantly, it provides the structure for the ongoing transition to formal risk management. Developments in this thesis are intended to enhance the CN Grade and Slope Stabilization Process while being consistent with the Protocol.

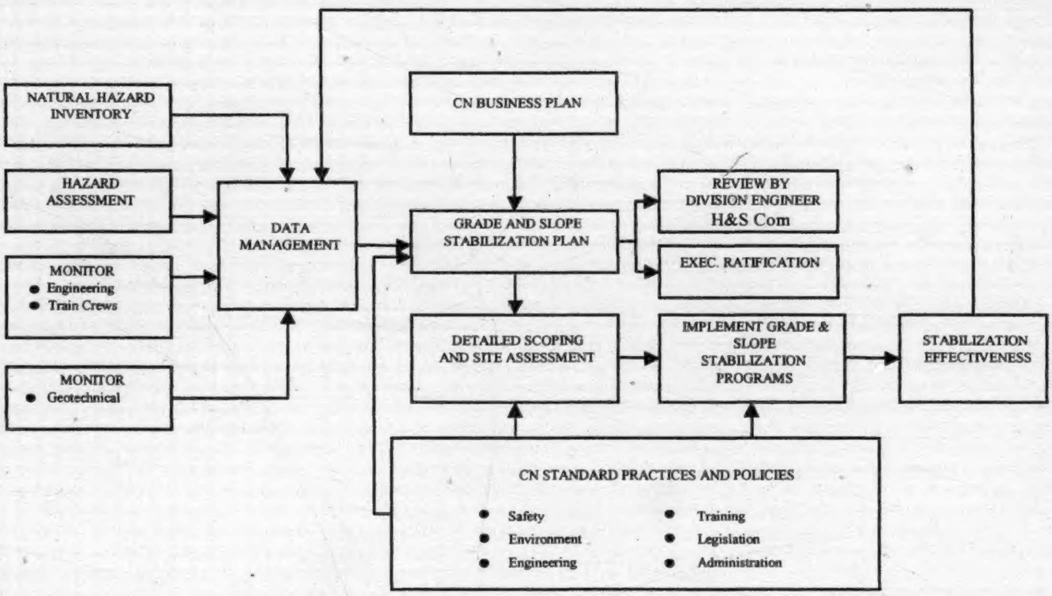

NATURAL HAZARD INVENTORY
HAZARD ASSESSMENT
MONITOR
Engineering
Train Crews
MONITOR
Geotechnical
DATA MANAGEMENT
CN BUSINESS PLAN
GRADE AND SLOPE STABILIZATION PLAN
REVIEW BY DIVISION ENGINEER
H&S Com
EXEC. RATIFICATION
DETAILED SCOPING AND SITE ASSESSMENT
IMPLEMENT GRADE & SLOPE STABILIZATION PROGRAMS
STABILIZATION EFFECTIVENESS
CN STANDARD PRACTICES AND POLICIES
Safety
Environment
Engineering
Training
Legislation
Administration

Figure 1-1 The CN grade and slope stabilization process (Keegan and Ruel, 1999)

1.1 Risk Management Methodology

Risk management is the process of making and implementing decisions that will minimize the adverse effects of accidental and business losses on an organization (Head and Horn, 1998). Ground hazards are considered sources of accidental loss. The approach employed for development of risk management is essentially a decision process involving the adaptation of the scientific problem solving techniques. The "problem" is exposure to accidental loss associated with ground hazards. Risk management of ground hazards, the solution, consists of the logical sequence of:

- Identifying and analyzing exposures to accidental and business losses that might interfere with the organization's basic objectives.
- Examining feasible alternative risk management techniques for dealing with the exposures.
- Selecting the apparently best risk management techniques.
- Implementing the chosen risk management techniques.

- Monitoring the results of the chosen techniques to ensure that the risk management program remains effective.

The Canadian Standards Association's "Risk Management: Guideline for Decision-Makers", CAN/CSA-Q850-97 (CSA, 1997) provides a practical framework for the development of a risk management system. The risk management methodology is developed in an iterative process as illustrated in Figure 1-2. The thesis completes step 2, Preliminary Analysis, and sets up the frame work to complete Step 3, Risk Estimation. The significant benefits to adopting the CAN/CSA-Q850-97 risk management approach are summarized as follows:

- The explicit consideration of risk helps decision-makers avoid costly losses.
- The risk management process provides a comprehensive, system approach to the analysis of the issue, which aids in ensuring that all aspects of the risk problem are identified and considered when making decisions.
- The approach incorporates perception of the acceptability of the risk into the decision process, providing for more informed decision-making and ensuring that the legitimate interests of all affected are considered. It incorporates a risk communication framework into the decision process, ensuring reasonable and effective communication.
- The use of a documented and transparent approach to decision-making provides the decision-maker(s) with a solid defense in support of decisions.
- A well-documented decision process makes decisions easier to explain and encourages the decision-maker to explore the rationale for decisions
- It provides a standardized set of terminology used to describe risk issues, thus contributing to better communication about risk issues.
- The use of a comprehensive risk management process can provide significant savings in health, time, and money.
- The process provides for an explicit treatment of uncertainty.
- The process is consistent and, in some areas, surpasses the standards set out in the Railway Safety Act: Safety Management Systems (1999).

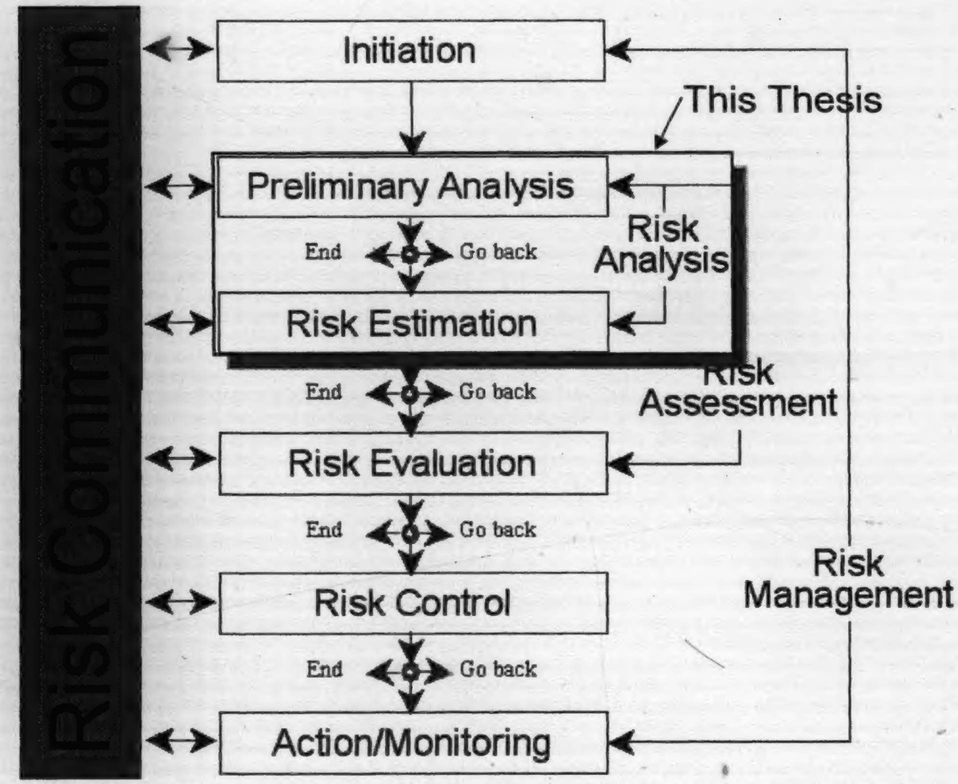

Risk Communication
Initiation
This Thesis
Preliminary Analysis
End
Go back
Risk Analysis
Risk Estimation
End
Go back
Risk Assessment
Risk Evaluation
End
Go back
Risk Management
Risk Control
End
Go back
Action/Monitoring

Figure 1-2 Steps in the Q850 Risk Management Decision Making Process – Simple Model (modified from CSA,1997).

The stated purpose and objectives of CAN/CSA-Q850-97 read as follows:

"The purpose of the Guideline is to provide a comprehensive decision process that will aid decision-makers in identifying, analyzing, evaluating, and controlling all types of risks, including risks to health and safety. The management of risk issues often entails priority-setting, due to limits on available resources. This process provides the information necessary to develop priorities.

The objective of risk management is to insure that significant risks are identified and that appropriate action is taken to minimize these risks as much as is reasonably achievable. Such actions are determined based on a balance of risk control strategies, their effectiveness and cost, and the needs issues, and concerns of stakeholder. Communication among stakeholders throughout the process is a critical element of this *risk management process. Decisions made with respect to risk issues must balance the technical aspects of risk with the social and moral considerations that often accompany such issues.*

This decision process is useful as a process for developing strategies to deal with potential risks before they occur. As such, it is an effective pre-loss planning tool.

It should be noted that while this Guideline requires that various analysis, consultations, and documentation be undertaken throughout the process, the level of effort extended to these should reflect the magnitude of the problem, the level of concern of stakeholders, and the resources available to the organization. For example, decisions internal to the organization may not require consultation with outside stakeholders; or if problems are straightforward or solutions evident, analysis may very well be limited. The decision-maker should make some judgment about the level of effort required to complete the steps in the risk management process, with reasonable efforts extended to complete the requirements of the process." (CSA,1997)

Besides being a good fit with the objective of this thesis, CAN/CSA-Q850-97 is the single Canadian standard recognized for development of a risk management methodology.

Note that CAN/CSA Q850-97 stresses the importance of risk communication for each step of the process.

1.2 Definitions

Unless otherwise defined, this thesis uses the glossary of definitions contained in CSA Q850-97 (CSA, 1997).

1.3 Purpose and Objectives

The purpose of this thesis is to progress the development of a formal risk management process for railway ground hazards in Western Canada for CN by completing the Preliminary Analysis step in the CAN/CSA-Q850-97 Risk Management: Guideline for Decision-Makers (CSA 1997). The purpose of a preliminary analysis is to define the basic dimensions of the risk problem and then undertake an analysis and evaluation of the potential risks.

The specific objectives of this thesis are to:

1. Develop a railway ground hazard and loss classification system.
2. Determine the nature, frequency, severity and annual costs associated with railway ground hazard scenarios in Western Canada on the CN track through an analysis of incidents, accident and loss records.
3. Develop a methodology to systematically characterize railway ground hazards for use in risk management.
4. Identify and classify railway ground hazard scenarios in Western Canada on CN track.
5. Characterize the railway ground hazard scenarios identified in CN Western Canada using the methodology developed.
6. Start the railway ground hazard risk information library for CN Western Canada.
7. Recommend specific steps to complete the development of a risk management system for railway ground hazards for CN Western Canada.

1.4 Thesis Structure

The structure of the thesis is as follows:

Chapter 2 presents a new railway ground hazard and loss type classification system, for use throughout the thesis, to practically categorize relevant railway ground hazards and the losses attributed to them.

Chapter 3 examines the available loss records from CN to determine the frequency, severity and annual loss attributable to CN's historical railway ground hazard losses.

Chapter 4 presents a new methodology to systematically characterize railway ground hazards for use in risk assessment and ultimately in risk management.

Chapter 5 describes the systematic process developed and employed by the author to populate the database of railway ground hazards in CN Western Canada; lists the forty railway ground hazard scenarios identified from the database; and describes the process used to characterize the identified railway ground hazard scenarios in CN Western Canada in the remaining chapters.

Chapter 6 characterizes the identified rock landslide hazard scenarios from the CN Western Canada ground hazard database using the methodology from Chapter 4.

Chapter 7 characterizes the identified debris landslide hazard scenarios from the CN Western Canada ground hazard database using the methodology from Chapter 4.

Chapter 8 characterizes the identified earth landslide hazard scenarios from the CN Western Canada ground hazard database using the methodology from Chapter 4.

Chapter 9 characterizes the identified subsidence hazard scenarios from the CN Western Canada ground hazard database using the methodology from Chapter 4.

Chapter 10 characterizes the identified overland / through flow erosion hazard scenarios from the CN Western Canada ground hazard database using the methodology from Chapter 4.

Chapter 11 characterizes the identified channelized flow hazard scenarios from the CN Western Canada ground hazard database using the methodology from Chapter 4.

Chapter 12 presents discussions, further work recommendations and conclusions from the thesis.

The process map, used in this thesis, to develop the risk analysis methodology for railway ground hazards is depicted in Figure 1-3.

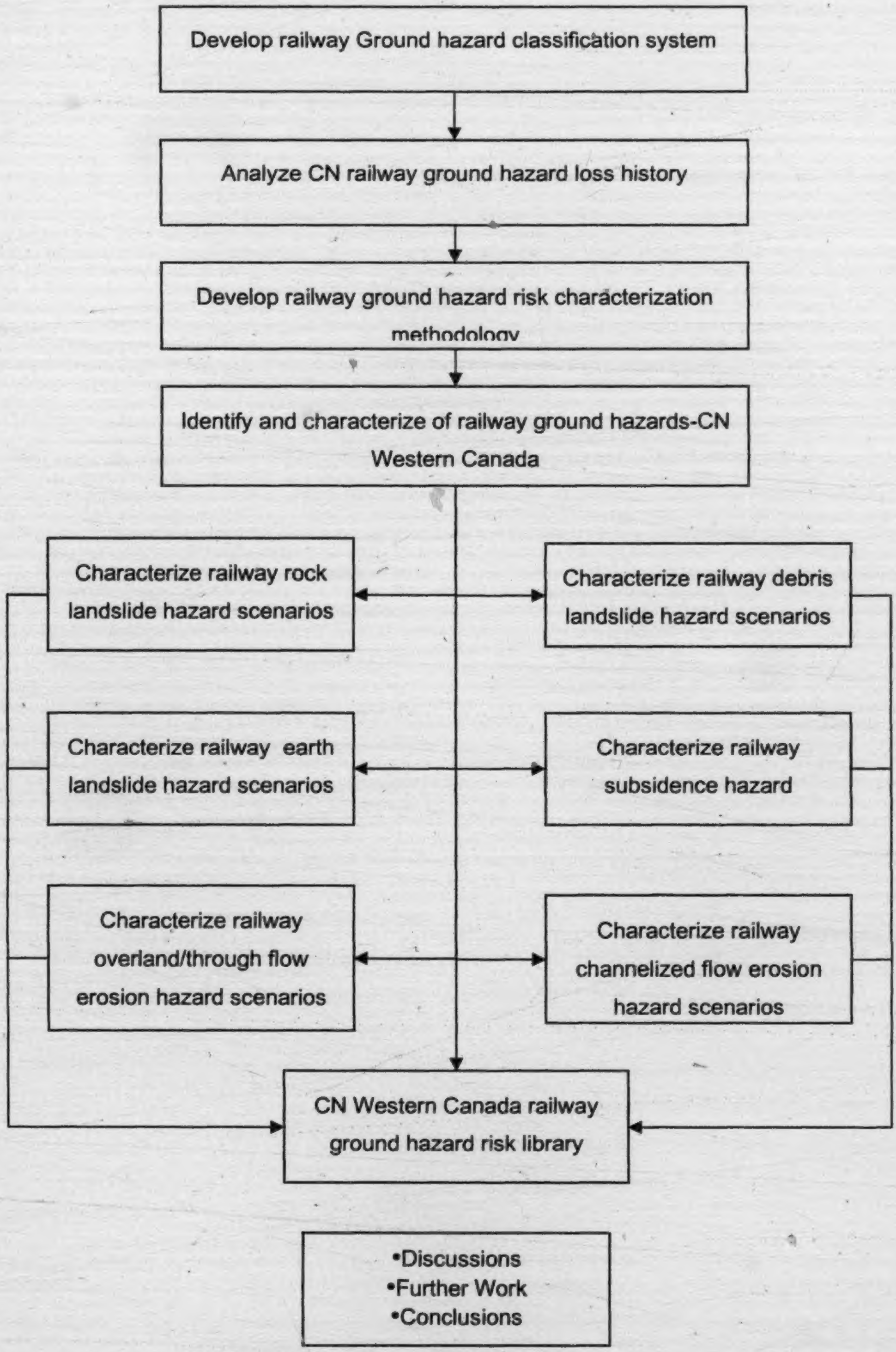

Develop railway Ground hazard classification system
Analyze CN railway ground hazard loss history
Develop railway ground hazard risk characterization methodology
Identify and characterize of railway ground hazards-CN Western Canada
Characterize railway rock landslide hazard scenarios
Characterize railway debris landslide hazard scenarios
Characterize railway earth landslide hazard scenarios
Characterize railway subsidence hazard
Characterize railway overland/through flow erosion hazard scenarios
Characterize railway channelized flow erosion hazard scenarios
CN Western Canada railway ground hazard risk library
•Discussions
•Further Work
•Conclusions

Figure 1-3 Thesis Map: Methodology for Risk Analysis of Railway Ground Hazards.

Chapter 2 Railway Ground Hazard Classification System

An essential task in the Preliminary Analysis step (CSA 1997) for the development of a risk management methodology for railway ground hazards is the development of a functional railway ground hazard classification system (RGHCS). This system is developed and described in this chapter. As a second task, the way in which CN Railway classifies and quantifies accidental losses is described at the end of this chapter.

The intent of the classification system is to provide a means to practically categorize relevant railway ground hazards for avoidance, control, or remediation. The RGHCS enables a structured framework for the risk management of railway ground hazards by providing:

- A means to systematically identify and characterize railway ground hazards as a means to describe and catalogue past occurrences and as a predictive tool for a hazard event in the identification of a railway ground hazard,
- A consistent and systematic organization of ground hazard information for use in both qualitative and quantitative risk analysis.
- A means to correlate between a ground hazard type and the appropriate risk control measures, and
- The systematic sharing and organization of experience and understanding gained by a variety of geotechnical practitioners.

This system is utilized in Chapter 3 to organize the historical loss records and in the remaining chapters to identify and characterize the railway ground hazard scenarios in CN Western Canada. The railway ground hazards classified in this chapter that are found to exist as a result of this research are further described and, when available, illustrated with case examples in Chapters 6 through 11.

2.1 General Classification

Level the author grouping of railway ground hazards is according to the material involved in the processes and Level II is according to the movement types that may occur. The approach is consistent with Cruden and Varnes (1996) for characterizing landslide types and processes extended here to cover the full spectrum of railway ground hazards of which landslides are but a subset. The two general railway ground hazard categories, based on the material types, are presented in Table 2-1.

Table 2-1 Level the author grouping of railway ground hazards based on materials

Category	Material(s) controlling the processes
Geotechnical	• Rock, soil and water
Ice and snow	• Ice

Table 2-2 provides a description of the level II subdivision in the classification system according to the movement type.

It is essential that the name given to a particular railway ground hazard incorporates the entire risk scenario that may result in loss. Commonly the chain of events that ultimately results in track failure involves more than one type of railway ground hazard event. For instance, river erosion often results in undercutting of a railway embankment leading to a landslide and track failure. These types of railway ground hazards are referred to here as *complex* railway ground hazards consistent with the terminology introduced by Cruden and Varnes (1996) for complex landslides. Similarly, complex ground hazards are named using the sequence of ground hazards that may lead to track failure. Although this chapter introduces a number of common, complex ground hazards in the landslide section there is no attempt to describe the complex ground hazards that include hazards from different level II categories. These are identified in subsequent chapters using the incident records (Chapter 4) and identification techniques (Chapter 5).

Sections 2.2 to 2.5 describe a further categorization of level II to the appropriate level to classify the individual railway ground hazard types. Section 2.6 presents a summary of the classification system.

Table 2-2 Subdivision of the classification system according to type of process.

Classification of Railway Ground Hazards		
Categories		Description
Level the author (material)	**Level II** (movement type)	
Geotechnical (rock, soil and water)	**Landslide**	Movement of a mass of rock, debris or earth down a slope (Cruden and Varnes 1996). (see Table 2-4 for railway landslide hazard classification)
	Subsidence	A vertical displacement of the track roadbed associated with compression or displacement of materials in the embankment or the underlying foundation. Settlement is a slow process resulting from compression, consolidation, plastic deformation or incremental dynamic liquefaction. Collapse is a rapid occurrence associated with vertical displacement into a void. (see Table 2-5 and Table2-6 for railway subsidence hazard classification)
	Hydraulic erosion	Erosion of soil particles or rock by the action of flowing waters. Erosion can result from overland, subsurface or sub-aqueous flow. (see Table 2-7 for railway hydraulic erosion hazard classification)
Ice and Snow (ice)	**Snow avalanche**	A volume of snow, usually more than several cubic metres, moved by gravity at perceptible speed. Snow avalanches may contain rock, broken trees, soil, ice or other materials. (CAA 2002(b)) (see Table 2-9 for railway snow avalanche hazard classification)
	Icing	Accumulation of ice either as an internal process of ice lens formation causing lifting of the track (frost heaves) or surface icing caused by groundwater discharge causing obstruction of the track or blockage of drainage. (see Table 2-9 for railway icing hazard classification)

2.2 Geotechnical – Railway Landslide Hazard Classification

The most common railway ground hazard type under the category of geotechnical is the landslide hazard. A railway landslide hazard is defined as a potential for loss to the railway caused by a landslide. This hazard exists if an existing or potential landslide can result in track failure rendering the track impassable to trains. Cruden and Varnes (1996) define a landslide as a movement of a mass of rock, debris or earth down a slope. Landslide types and processes have been described on the basis of type of material and type of movement categorization by Varnes (1978) and revised by Cruden and Varnes (1996). Both articles had the expressed intention of "developing and attempting to make more precise a useful vocabulary of terms by which…[landslides]… may be described". They review the range of landslide processes and provide a vocabulary for describing the features of landslides relevant to their classification for avoidance, control, or remediation. This approach is therefore aptly suited to classify and characterize railway landslide ground hazards and addresses the associated risks. The various geologic material types and landslide movement types are summarized in Table 2-3.

Table 2-3 Summary of landslide geologic material and movement types (revised from Cruden and Varnes, 1996)

***GEOLOGIC MATERIAL* Types**

Rock (R)	A hard or firm mass that was intact and in its natural place before the initiation of movement
ENGINEERING SOILS: (S)	
Debris (D)	Contains a significant proportion of coarse material; 20 to 80 percent are larger than 2 mm, the remainder is less than 2 mm
Earth (E)	Material in which 80 percent or more of the particles are smaller than 2 mm, the upper limit of sand-size particles

***LANDSLIDE MOVEMENT* Types**

Fall (F)	A mass is detached from a slope and descends either freely or by leaping, bouncing and rolling with little shear displacement
Topple (T)	The rotation of a mass about a point located either below the mass or in the lower part of it
Slide (Sl)	A slide occurs when there is shear strain or displacement across a surface or surfaces. In a slide, the material in motion may consist either of a few blocks with some deformation or many smaller blocks with great deformation. Each of these sliding movements can be categorized as being rotational or translational.
Spread (Sp)	An extension of a soil or rock mass, accompanied by a general subsidence of the fractured mass into the softer material beneath. These occur either as distributed movements without any defined shear surface, as a plastic flow zone or as movements involving fracturing and extension of rock or soil due to liquefaction or plastic flow of underlain softer material.
Flow (Fw)	Flows occurring in debris or earth resemble the movements of a viscous fluid.

Either of the two materials can undergo any one of the five types of landslide movements or a combination of two or more of them. The terms used should describe the displaced material in the landslide before it was displaced. Thus, a fall can be a rock fall, a debris fall or an earth fall and a slide can be a rock slide, debris slide or an earth slide.

The railway landslide hazard types are listed in Table 2-4. This list classifies railway landslide hazards utilizing the type of material as the level III categorization and type of movement as the level IV categorization. This list was compiled from a review of the case records and the railway landslide experience of the author. Where the landslide hazard is complex, involving more than one hazard type, it is classified according to the ultimate movement type that is realized at track level. For instance, a rock slide-rock fall is classed as a rock fall if the rock fall directly affects the railway. Identifying the material of the first movement type has utility in ground hazard identification, as it can be associated to the pre-event material type and landform. For instance, hazards can be identified directly from terrain analysis.

Table 2-4 **Classification of railway landslide ground hazards**

First Movement Type	*Second Movement Type*	*Third Movement Type*
ROCK LANDSLIDES		
ROCK FALLS:		
Rock fall		
Rock topple	Rock fall	
Rock topple	Rock slide	Rock fall
Rock slide	Rock fall	
ROCK TOPPLES		
Rock topple		
ROCK SLIDES:		
Rock slide		
Rock topple	Rock slide	
DEBRIS LANDSLIDES		
DEBRIS FALLS		
Debris fall		
Debris slide	Debris fall	
DEBRIS SLIDES		
Debris slide		
DEBRIS FLOWS		
Debris flow		
Rock slide	Debris flow	
EARTH LANDSLIDES		
EARTH FALLS		
Earth fall		
Earth slide	Earth fall	
EARTH SLIDES		
Earth slide		
Earth flow	Earth slide	
Earth spread	Earth slide	
EARTH FLOWS		
Earth flow		
Earth slide	Earth flow	
EARTH SPREADS		
Earth spread		

2.3 Geotechnical –Railway Subsidence Hazard Classification

A railway subsidence hazard is defined as a downward displacement of the track associated with compression or displacement of materials in the ballast, sub grade, embankment or underlying foundation. Level III categorization of subsidence is based on the long-term rate of movement. Settlement is a slow process resulting from compression, consolidation, plastic deformation or incremental dynamic liquefaction. These settlement processes are used for the level IV categorization as described in Table 2-5. Conversely, collapse is a sudden occurrence usually associated with vertical displacement into a void. As such, level IV categorization of collapse hazards is based on the process that has either caused the void to form or caused the ground to suddenly lose all its strength as in the case of liquefaction. Types of railway collapse hazards are listed and described in Table 2-6.

Table 2-5 **Classification of railway subsidence settlement hazards.**

Categories		Description
Level III (rate of movement)	**Level IV** (process)	
Settlement (slow downward movement)	Consolidation	The adjustment of a saturated soil foundation in response to increased load. Involves the squeezing of water from the pores and a decrease in void ratio (AGI, 1976). This class refers to soils of low permeability such as organic terrain (muskeg) and soft compressible clays where drainage and thus settlement is slow. Fills placed across this ground can settle for many years, responding to the consolidation characteristics of organic or clay soils and to compositional changes (organic decay) occurring in the foundation.
	Compression	A system of forces or stresses that tends to decrease the volume or shorten a substance, or the change of volume produced by such a system of forces (AGI 1976). Differential compression and settlement associated with poorly compacted or dumped fills. Differential compaction occurs in fills placed by dumping with little or no mechanical stabilization through compaction. Under the applied load of trains, the weight of the overburden, and loads resulting from wetting and drying, compaction occurs at differing rates resulting in irregular settlement. Heterogeneity of the fill can be a contributing factor. Such processes can remain active for many years.
	Sub-grade plastic deformation	Incremental plastic deformation and settlement of the track resulting from local over-stressing and incremental plastic deformations of clay sub-grades from repetitive train loads. Plastic deformation occurs at the top of the sub-grade where the loads are highest. It begins with the squeezing out of the sub-grade from beneath the tracks giving rise to depressions. Degradation of soil strength due to water collecting in depressions accelerates the plastic deformation.
	Subgrade dynamic liquifaction	Incremental differential settlement, localized to the track ballast and sub-grade, occurs in saturated fine-grained non-cohesive soils or fouled ballast and is the result of dynamic liquefaction induced by cyclic train loading. Process leads to additional ballast fouling, formation of ballast pockets and ultimately the formation of mud spots. Commonly associated with ballast at the end of its design life, ballast pockets, high impact locations (such as joints, bridge approaches, switches, diamonds or crossings), and the thawing of ice lenses at frost heave locations.

Table 2-6 **Classification of railway subsidence collapse hazards.**

Categories		Description
Level III (process)	**Level IV** (process)	
Collapse (rapid downward movement)	Piping or dissolution voids	Collapse into remnant voids formed as the result of piping in soils or dissolution in rocks. The soil or rock properties have to be such that voids have propensity to remain open under the track structure. Piping or dissolution that leads directly to failure of the track structure is classed as hydraulic erosion.
	Culvert failure	Collapse into a void caused by a failed culvert. Culverts can fail due to corrosion or physical damage such as a pull-apart at a joint. The culvert either collapses into itself or a void is formed outside of the culvert when soil trickles in from the top, is sucked in from the bottom by negative pressure from flowing water or is removed through erosion by water flowing outside of the culvert.
	Collapsing soils	Soil exists in the subgrade that is susceptible to a large and sudden reduction in volume upon wetting. Collapsing soils in the track sub-grade collapse upon wetting, triggering track failure.
	Timber deterioration	Collapse into voids formed by rotting buried timber structures such as trestles, corduroy or abandoned timber box culverts common to railway fills.
	Voids in rock fill	Collapse into voids inherent in large uniform graded rock fill embankments.
	Liquefaction	Collapse into underlying liquefied soil. Most likely triggered by cyclic earthquake loading.
	Burrowing Animals	Collapse into voids formed in the sub grade by burrowing animals
	Utilities	Collapse into voids formed under the sub grade by pipe utilities.
	Mining	Collapse into voids formed under the sub grade by mining works.

2.4 Geotechnical – Railway Hydraulic Erosion Classification

Hydraulic erosion involves removal of soil particles or rock by the action of flowing waters. A railway hydraulic erosion hazard is defined as a potential for loss to the railway caused by hydraulic erosion and thus only exists if existing or potential hydraulic erosion can result in track failure. Level III categorization of railway hydraulic erosion hazards is based on the slope hydrologic cycle divided into overland flow, through flow and sub-aqueous flow. Level IV categorization is based on process type as described in the railway hydraulic erosion hazard classification system presented in Table 2-7 with a sub reference to Table 2-8 for level V categorization of channelized flow erosion hazards.

Table 2-7 Classification of railway hydraulic erosion hazards.

Categories		Description
Level III (hydrologic cycle)	**Level IV** (process type)	
Overland flow (runoff)	Slope wash	Occurs when rainfall impacts and loosens soil particles, which then move with the water. Can occur in sheets or rills, and can initiate gullies.
	Gully erosion	Initiation of a channel on a sloping surface caused when the erosive forces of concentrated overland flows surpasses the resistance of the surface being eroded. Once water is focused into channels, this positive feedback process promotes continued evolution of channel networks at the expense of unconfined sheet flow (Ritter, 2002). Gully erosion by overtopping of a railway embankment commonly results in catastrophic failure of the rail grade as it involves the sudden release of impounded water comparable to a dam burst scenario.
Through flow	Seepage Erosion	Occurs when exit velocity of groundwater is sufficient to cause particle erosion. As erosion occurs, the hydraulic gradient is increased, which further increases exit velocities and seepage erosion.
	Piping	Piping occurs when water flowing through material opens a tunnel or pipe that remains open and continues to erode material. Piping is dependent on the soil permeability, preferential flow paths, ability to maintain an arched opening, chemical makeup and the erosive nature of the material. As piping progresses, the flow path shortens, the hydraulic gradient increases and the piping accelerates up the flow path.

Categories		Description
Level III (hydrologic cycle)	**Level IV** (process type)	
	Culvert erosion	Processes that result in internal hydraulic erosion around a culvert due to: 1. Water running out of the culvert due to a corrosion or abrasion hole, a pull-apart at a joint or poorly sealed joints. 2. Soil being sucked in through an opening in the culvert by negative pressure from flowing water in the culvert. 3. Water running along the preferential flow path outside of the culvert driven by a surcharge at the inlet of the culvert due to a backup into the culvert caused by debris or ice blockage at either the inlet or outlet, an under capacity culvert or a buoyancy failure of a surcharged inlet.
	Dissolution	Erosion of voids in rock developed by solution generally in limestone, dolomite or gypsum. Associated with karst topography
Sub-aqueous flow	Channelized flow erosion	Erosion of soil particles or rock by channelized flowing water such as streams, rivers and ocean currents. (see Table **2-8** for level V categorization of channelized flow erosion)
	Wave action erosion	Erosion by wave action along shorelines of ponds, river, lakes and oceans.

In regions such as British Columbia where the railways are routed along river valleys, channelized flow erosion, primarily river erosion, has proven to be a primary railway ground hazard or a significant component of a complex ground hazard such as river erosion-earth slide. Because of this high frequency of occurrence and the diversity of river processes that cause them, a level V categorisation of channelized flow erosion hazards was developed and described in Table 2-8. Further description and characterization is provided in Chapter 5.

Table 2-8 Classification of railway sub-aqueous channelized flow erosion.

Category		**Description**
Level IV (process type)	**Level V** (process type)	
Sub-aqueous channelized flow	Channel Aggradation	Raising the level of streambed when sediment supply exceeds sediment transport capacity. Can lead to burial of a bridge, increased loading on a bridge especially during flooding, erosion due to channel widening, increased likelihood of flooding, debris blockage and bridge overtopping. Aggradation is also a leading cause of stream avulsion.
	Channel Degradation	General lowering of the channel over a reach of the stream of river. Often in response to a decrease in sediment supply, the down-cutting of an immature river system or down-cutting into landslide material.
	Local Scour	Localized deepening of the channel by erosion caused by vortexes created by obstructions, increased velocity and downward spiralling currents on the outside bend of a meander or differentially erodible material on the channel bottom. Obstructions can be manmade such as bridge piers or abutments or natural such as bedrock knobs, boulders, gravel bars, or log jams.
	General Scour	Localized lowering across a channel due to reduction in the effective width of the channel. Constrictions can be manmade such as rock berms or bridge approach fills, piers and abutments or naturally occurring in the case of alluvial fans, colluvial fans or landslides that encroach and reduce the effective channel width.
	Ice or log jams	Localized lowering across a channel due to reduction in the effective depth of the channel caused by excessive build up of ice or floating debris on the surface. Can also cause avulsion and flooding. Note that damage can also occur to bridges either from impact of the ice or debris or from excessive forces on the bridge caused by the impeded flow.
	Encroachment	Lateral shift in the stream bank towards the rail grade where the track runs parallel to a stream valley.
	Bank Erosion	Localized loss of the bank material. Occurs commonly during high water on unprotected and erodable riverbanks due to stream scour along the toe that undermines the bank and the material above sloughs off or when rapid flow draw down after floods cannot be matched by draw down of moisture in bank material. Poorly consolidated silts, sands and gravels erode quicker than bedrock, cobbles, boulders or cohesive material. Locations on the outside bend of a meander are more susceptible to bank erosion, as velocities are usually greater and flow direction spirals downward.

Category		Description
Level IV (process type)	Level V (process type)	
	Avulsion	Sudden abandonment of a water course (includes bankfull channel, ditch or culvert or bridge opening), in favour of another. Common in watersheds with beaver activity, poorly defined or clogged channels, alluvial fans and the floodplains of large anabranching and braided streams. Can be total or partial abandonment of one channel for another.

2.5 Railway Snow and Ice Hazards Classification

Railway snow and ice hazards involve processes of snow and ice that can result in track failure. Level II railway snow and ice hazards are grouped by process as either snow avalanches with level III categorization according to CAA (2002(b)) or as accumulation of ice or snow referred to as icing with level III classification according to whether the icing is above or below surface. The railway snow and ice hazard classification system is presented in Table 2-9 and characterized further in Chapter 5.

Table 2-9 **Classification of railway ice and snow hazards.**

Category		Description
Level II (process)	Level III (process)	
Snow Avalanche	Slab avalanche	An avalanche in which a plate or slab of cohesive snow begins to move as a unit before breaking up. Most large and long-running avalanches start as slab avalanches.
	Loose snow avalanche	An avalanche in which a small volume (<1m3) of low-cohesion snow fails and begins to move down slope, setting additional snow in motion and forming an inverted V-shape on the slope. Also called a point release avalanche. Dry loose snow avalanches are usually small. Wet loose snow avalanches can be small or large.
	Dry snow avalanche	Dry snow avalanches – no liquid water between particles – usually run faster and farther than wet snow avalanches in the same path and tend to overrun minor terrain features. Avalanches can start in dry snow and deposit as dry or wet snow farther down the slope.

Category		Description
Level II (process)	**Level III** (process)	
	Wet snow avalanche	Wet snow avalanches, which contain liquid water between particles, usually move slower than dry snow avalanches in the same path and tend to be channelled and diverted by terrain features. On gentle slopes or level terrain, wet snow avalanches may spread or split into tongues, the directions of which are difficult to predict. The run-out zone may differ for dry and wet avalanches and caution must be used in using past events to determine potential run-out.
	Slush flows	Slush consists of snow that is soaked with water. Slush flows start on gentle slopes, often 5° to 25°, where the ground is poorly drained, and the supply of water is abundant due to rain or snowmelt. Slush flows move like liquid and can run onto level terrain. Slush flows are rare, except in northern latitudes such as Canada.
Icing	Frost heaves	Subsurface accumulation of ice lenses such that there is an upward heave of the ground surface. Frost heave development requires the appropriate combination of freezing penetration, free water and frost susceptible soils (SM or ML).
	Surface icing	Surface accumulations of ice or snow in sufficient quantities to affect track failure. Ice accumulation is often the result of groundwater springs during freezing conditions and is common in tunnels, culverts and cut sections.

2.6 Summary of Railway Ground Hazard Classification

A reference summary of the railway ground hazard classification system described in this chapter is presented in Table 2-10, Table 2-11 and Table 2-12. This classification system is utilized to asses and categorize the CN historic loss records in Chapter 4. In Chapter 5 these hazards are described in more detail and supported with case examples and statistics obtained from Chapter 4. Chapter 6 is dedicated to approaches for the identification and information management of these hazards.

Table 2-10 **Summary of railway geotechnical hazards (Landslides and Subsidence)**

Railway Geotechnical Hazard Classification

Level I	Level II	Level III	Level IV	Abbrev.
Geotechnical (rock, soil and water)	**Landslides**	**Rock landslides**	Rock fall	RF
			Rock topple-rock fall	RT-RF
			Rock topple–rock slide–rock fall	RT-RSI-RF
			Rock slide-rock fall	RSI-RF
			Rock topple	RT
			Rock slide	RSI
			Rock topple-rock slide.	RT-RSI
		Debris landslides	Debris fall	DF
			Debris slide-debris fall	DSI-DF
			Debris slide	DSI
			Debris flow	DFw
			Rock slide-debris flow	RSI-DFw
		Earth landslides	Earth fall	EF
			Earth slide-earth fall	ESI-EF
			Earth slide	ESI
			Earth flow-earth slide	EF-ESI
			Earth spread-earth slide	ESp-ESI
			Earth flow	EFw
			Earth slide-earth flow	Esl-EFw
			Earth spread	ESp
	Subsidence	**Settlement**	Consolidation	Cn
			Compression	Cm
			Sub grade plastic deformation	SPD
			Sub grade dynamic liquefaction	SDL
		Collapse	Piping or dissolution voids	PD
			Collapsing soils	CS
			Culvert failure	CF
			Timber deterioration	TD
			Voids in rock fill	VRF
			Liquefaction	L
			Burrowing Animals	BA
			Pipe Utilities	PU
			Mining	M

Table 2-11 **Summary of railway geotechnical hazards (Hydraulic Erosion)**

Railway Geotechnical Hazard Classification					
Level I	Level II	Level III	Level IV	Level V	Abbrev.
Geotechnical (rock, soil and water)	**Hydraulic Erosion**	**Overland flow erosion**	Slope wash		SW
			Gully erosion		GE
		Through flow erosion	Seepage erosion		SE
			Piping		P
			Dissolution		D
		Sub-aqueous flow erosion	Channelized flow erosion	Channel aggradation	ChA
				Channel degradation	ChD
				Local scour	LS
				General scour	GS
				Ice or log jams	(I or L)J
				Encroachment	En
				Bank erosion	BE
				Avulsion	Av
			Wave erosion		WE

Table 2-12 **Summary of railway ice and snow hazards**

Railway Ice and Snow Hazard Classification			
Level I	Level II	Level III	Abbrev.
Ice and snow (ice)	**Snow avalanche**	Slab avalanche	SA
		Loose snow avalanche	LSA
		Dry snow avalanche	DSA
		Wet snow avalanche	WSA
		Slush flow	SF
	Icing	Frost heaves	FH
		Surface icing	SIc

2.7 Types of Railway Loss

The railway quantifies loss associated with railway ground hazards as well as accidental loss associated with other hazards in terms of injury or fatality; train accidents (primarily derailments) and clean up; train service disruption; and hazard mitigation. Traditional types of loss such as personnel, net income, property, market share, liability and environmental loss are indirectly correlated to these four types as indicated in Table 2-13.

Table 2-13 Association between railway loss types and traditional loss type measures

Railway loss types	Correlated traditional loss types
Injury and fatality	Personnel loss
Train accidents and cleanup	Property, net income, market share, liability, environment
Train service disruption	Net income, market share
Hazard Mitigation	Net income, environment

Records of net income, market share, liability and environment loss are for the most part either intangible or not available for this review. None the less, because of the correlation established in Table 2-13, the relative value of these traditional loss types is reflected in the railway loss measures.

2.8 Summary

The classification system developed standardizes the identification of railway ground hazard types. It groups the possible hazard events according to the ground conditions and processes involved. Besides labelling the hazard, classifying in this manner provides an immediate understanding or characterization of the mechanics of these hazards. The Railway ground hazards are initially grouped into landslides, subsidence, hydraulic erosion and snow and ice hazards.

Landslide hazard classification uses Cruden and Varnes (1996) system to group the potential slope movements according to the predominant material and movement type expected.

Railway subsidence hazards refer to potential downward movement of the track. Settlement hazards involve slow subsidence over time due to continuous or incremental vertical movements. Collapse hazards involve rapid vertical displacement of the track due usually to collapse of a void but also include liquefaction. The individual subsidence hazards are classified according to the primary process causing the subsidence. In the case of subsidence hazards the controlling material types are indicated in the description of each hazard.

Railway hydraulic erosion hazards involve removal of soil particles or rock by the action of flowing waters. The initial grouping of railway hydraulic erosion hazards is based on the division of the slope hydrologic cycle into overland flow, through flow and sub-aqueous flow. The individual hazards are classified according to the predominant process type causing the flow erosion. Due to the high frequency of occurrence and the diversity of river processes, channelized flow erosion hazards are further subdivided according to the predominant channelized flow erosion process expected to cause the hazard event. Channelized flow erosion hazard events have proven to be a significant component of a number of complex ground hazard events such as channelized flow erosion -earth slide.

The snow avalanche hazards classification is taken from the Canadian Avalanche Association guidelines (CAA, 2002(b)). The icing hazard classification system is new. The railway ground hazard risk characterization system methodology developed in this thesis includes ice and snow hazards.

In compliance with CSA Q850-97, and to complete a review of the railway loss records and understand the consequences associated with railway ground hazards, the last section of Chapter 2 describes how the railways classify and measure loss, and associates these loss types to loss types used in conventional risk management taken from Head (1998). Essentially railways measure accidental loss in terms of safety (injury and fatalities), train accidents and cleanup (derailments), train service disruptions and the costs of hazard mitigation.

Chapter 3 Analysis of CN Railway Ground Hazard Loss History

3.1 Introduction

This chapter examines the available loss records from CN to determine the frequency, severity and annual loss attributable to CN's historical railway ground hazard losses. This exercise is consistent with Section 5.3 Identifying Hazards Using Risk Scenarios under the Preliminary Analysis Step from CAN/CSA-Q850-97 (CSA 1997). The railway classification system and CN railway loss types developed in Chapter 3 are used here to classify the ground hazards and ground hazard events into their appropriate hazard categories.

3.2 Loss Data Sources

To complete the review of loss records at CN, a master database of train accidents, major track outages and mitigation was compiled. The three main sources of historical ground hazard loss records used in this chapter include:

- Train accident records from the CN's C.A.R.E.S. database
- CN Geotechnical files
- CN's Natural Hazard Incident reporting database.

Following is a description of each of these information sources.

CN Accident Reporting and Evaluation System (C.A.R.E.S.)

The safety and loss records at CNR are contained in the CN Accident Reporting and Evaluation System (CARES, 2001). CARES is a computerized accident reporting system, used to capture information with respect to accidents and personal injuries. It is important to state that accidents which have an estimated direct cost of greater than $10,000 are required by law to be reported to the Canadian Federal Railway Administration (FRA) and are therefore part of the public domain. The three main categories in CARES are train movement accidents, personal injuries and crossing accidents. Coding used to filter out specifically ground hazard related train movement accidents and personnel injuries is presented in Table 2-1 taken from CARES (2001).

The costs that are reported to the CARES system are only damage costs related to railway property as a result of an accident. Reportable damage includes labour costs and all other costs to repair or replace in kind damaged on-track equipment, signals, track, track structures or roadbed. Reportable damage does not include the cost of clearing the wreck; however, additional damage to the above listed items caused while clearing the wreck is included in the damage estimate. It therefore does not include more intangible losses such as costs of injury and fatality, lost or damaged locomotives or rail cars, damaged or lost lading, lost revenue or any liability losses. In most cases the intangible losses are an order of magnitude higher than the direct costs but are near impossible to determine with certainty or consistency.

Table 3-1 CARES cause coding associated with ground hazard events

Accident Cause Code	Description
Train Movement Accident	
M101	**Environmental Conditions – snow, ice, mud, gravel, coal on tracks**
M103	**Environmental Conditions – flood**
T001	**Roadbed – settled or soft track**
T002	**Roadbed – Washout/rain/slide/flood/snow/ice**
T003	**Roadbed – other defects**
Personal Injury Accident	
0204	**Material falling in excavations (struck by)**
0205	**Flying material (struck by)**

0207	**Acts of God (struck by)**
0302	**Excavation collapsed (caught in)**
0303	**Hole (caught in)**
0408	**On track equipment (caught on)**
0409	**Material handling equipment (caught on)**
0410	**Locomotive (caught on)**
0610	**Roadbed (slip)**

CN Geotechnical Records

The CN geotechnnical files have been kept from approximately 1971 by CN's Geotechnical Engineers. The geotechnical files are essentially project files containing documentation of ground hazard mitigation. Until recently they were exclusively paper files referenced by railway mileage and subdivision. The files are relatively incomplete and are used mainly as reference material.

CN's Natural Hazard Incident reporting

There are two sources of ground hazard incident reporting used in this review. The first source is contained in the Peckover (1972) report produced in response to the formal inquiry into safety of operation in the mountain territory of Canadian National and Canadian Pacific (RTC,1973) by the Railway Transport Committee, resulting from a fatal derailment at Mileage 118.9 on CNR's Ashcroft Subdivision on February 15, 1971.

Amongst other things, the Peckover report provides a summary of injuries and fatalities between 1937 and 1971 on CN and CPR main railway corridors in BC resulting from landslides. As well, it provides a summary of estimated costs of landslide incidents on CNR for the period 1966 to 1970 inclusive. Regrettably none of the backup documentation used to produce these summary tables could be found in CN's archives. Relevant excerpts from this report are in an Excel © workbook entitled "Ground Hazard casualties 1937 to 1971.xls" available through Appendix A.

The second source is a reporting system started in 1995 on the Yale Subdivision set up to compliment the development of the CN Rockfall Hazard and Risk Assessment (CNRHRA) system (Abbott et al, 1998). It does have the facility to report all types of ground hazard events however this has not been fully utilized to date. Although the most consistent reporting has been of rockfall events from the Yale and Ashcroft Subdivision it was extended to include other CN subdivisions in BC in recent years including BC Rail in 2005.

3.3 Comparison of Railway Ground Hazards to other Railway Hazards

The first step in the analysis of historical loss records is to compare the frequency and severity of loss associated with railway ground hazards against that associated with other railway hazards. This comparison was completed using records of all train accidents on CN mainline track from 1996 to 2001 extracted from CN's C.A.R.E.S. safety and loss database. is a summary table of these results subdivided into four main cause groups namely Engineering, Mechanical, Transportation and a number of defined categries grouped as miscellaneous. Each main group is broken out into the specific cause code. This database is contained in an Excel © workbook entitled "All acid all DIV 92-2001 mainline only.xls" available through Appendix A.

C.A.R.E.S. Cause Code	Accidents	*Frequency* (acc./year)	Costs (1996-2001)	*Severity* (cost/acc.)	*Annual Costs* (frequency x severity))	Total duration Outages one day or more (days)	Number of outages one day or more	Average annual duration of outages one day or more (days per year)	Average Duration/ Incident (days)
Eng : Frogs, Switches and track appliances	69	11.5	$ 1,356,949	$ 19,666	$ 226,158	7	5	1.2	1.40
Eng : Other way and structure	4	0.7	$ 135,003	$ 33,751	$ 22,501	0	0	0	0.00
Eng : Rail, Joint Bar and Rail Anchoring	105	17.5	$ 34,265,519	$ 326,338	$ 5,710,920	35	22	5.8	1.59
Eng : Track geometry	161	26.8	$ 14,945,338	$ 92,828	$ 2,490,890	93	43	15.5	2.16
Eng : Roadbed	**48**	**8.0**	**$ 18,966,348**	**$ 395,132**	**$ 3,161,058**	**50**	**18**	**8.33**	**2.78**
Eng : Signal and communication	7	1.2	$ 1,405,847	$ 200,835	$ 234,308	0	0	0.0	0.00
Engineering Causes	**394**	**65.7**	**$ 71,075,804**	**$ 180,393**	**$ 11,845,834**	**185**	**88**	**30.8**	**2.10**
Mech : Brakes	26	4.3	$ 3,193,235	$ 122,817	$ 532,206	16	10	2.7	1.60
Mech : Body	20	3.3	$ 923,464	$ 46,173	$ 153,911	7	5	1.2	1.40
Mech : Coupler and draft system	31	5.2	$ 451,110	$ 14,552	$ 75,185	8	8	1.3	1.00
Mech : Truck components	40	6.7	$ 4,586,528	$ 114,663	$ 764,421	5	4	0.8	1.25
Mech : Axles and journal bearings	73	12.2	$ 9,260,287	$ 126,853	$ 1,543,361	22	20	3.7	1.10
Mech : Wheels	57	9.5	$ 10,504,538	$ 184,290	$ 1,750,756	39	18	6.5	2.17
Mech : Locomotives	2	0.3	$ 6,355	$ 3,178	$ 1,059	0	0	0.0	0.00
Mech : Doors	2	0.3	$ 63,800	$ 31,900	$ 10,633	2	2	0.3	1.00
Mech : General mechanical and electrical failures	4	0.7	$ 439,045	$ 109,761	$ 73,174	2	1	0.3	2.00
Mechanical Causes	**255**	**42.5**	**$ 29,428,362**	**$ 115,405**	**$ 4,904,727**	**101**	**68**	**16.8**	**1.5**
Trans : Brakes, use of	34	5.7	$ 2,466,125	$ 72,533	$ 411,021	5	4	0.8	1.25
Trans : Employee physical condition	4	0.7	$ 589,553	$ 147,388	$ 98,259	1	1	0.2	1.00
Trans : Flagging, fixed, hand and radio signals	10	1.7	$ 445,310	$ 44,531	$ 74,218	1	1	0.2	1.00
Trans : General switching rules	68	11.3	$ 432,526	$ 6,361	$ 72,088	9	8	1.5	1.13
Trans : Main track authority	18	3.0	$ 650,697	$ 36,150	$ 108,450	0	0	0.0	0.00
Trans : Train handling / train make-up	85	14.2	$ 3,231,887	$ 38,022	$ 538,648	19	14	3.2	1.36
Trans : Speed	26	4.3	$ 2,084,075	$ 80,157	$ 347,346	6	4	1.0	1.50
Trans : Switches, use of	65	10.8	$ 1,963,545	$ 30,208	$ 327,258	9	9	1.5	1.00
Transportation Causes	**310**	**51.7**	**$ 11,863,718**	**$ 38,270**	**$ 1,977,286**	**50**	**41**	**8.3**	**1.2**
Misc : Misc. Human Factor	53	8.8	$ 456,888	$ 8,621	$ 76,148	0	0	0.0	0.00
Mech : Mechan. Empl. human factor	2	0.3	$ 335,356	$ 167,678	$ 55,893	1	1	0.2	1.00
Misc : Environmental conditions	44	7.3	$ 1,503,430	$ 34,169	$ 250,572	8	6	1.3	1.33
Misc : Loading procedures	34	5.7	$ 432,858	$ 12,731	$ 72,143	7	5	1.2	1.40
Misc : Highway- rail grade crossing accidents	51	8.5	$ 1,836,457	$ 36,009	$ 306,076	10	7	1.7	1.43
Misc : Unusual operational situations	108	18.0	$ 1,671,884	$ 15,480	$ 278,647	6	5	1.0	1.20
Misc : Other miscellaneous	138	23.0	$ 4,256,094	$ 30,841	$ 709,349	27	16	4.5	1.69
Miscellaneous Causes	**430**	**71.7**	**$ 10,492,967**	**$ 24,402**	**$ 1,748,828**	**59**	**40**	**9.8**	**1.5**
TOTALS:	**1389**	**231.5**	**$ 122,860,851**	**$ 88,452**	**$ 20,476,675**	**395**	**237**	**65.8**	**1.7**

Table 3-2 CN Mainline Accidents System –Wide from C.A.R.E.S 1996-2001

The cause code that is primarily used to capture railway ground hazard incidents as described in Chapter 3 is *Eng. Roadbed.* It is possible that some of the incidents coded as *Eng. Track Geometry* or *Misc. Environmental Conditions* are in part due to ground hazards. However, this was not examined in this exercise.

The causes were analyzed first by frequency (accidents/year), severity (direct cost/accident) and loss (direct costs/year) and secondly by service disruption in terms of significant outages of one day or more.

Figure 3-1 presents the annual frequency of train accidents between 1996 and 2001 in terms of accidents per year subdivided into the four main cause groups. In the same chart Engineering caused accidents are broken down into the individual cause codes. Note that Eng. Roadbed causes, which represent the bulk of ground hazard caused accidents had a relatively low frequency of 8 per year.

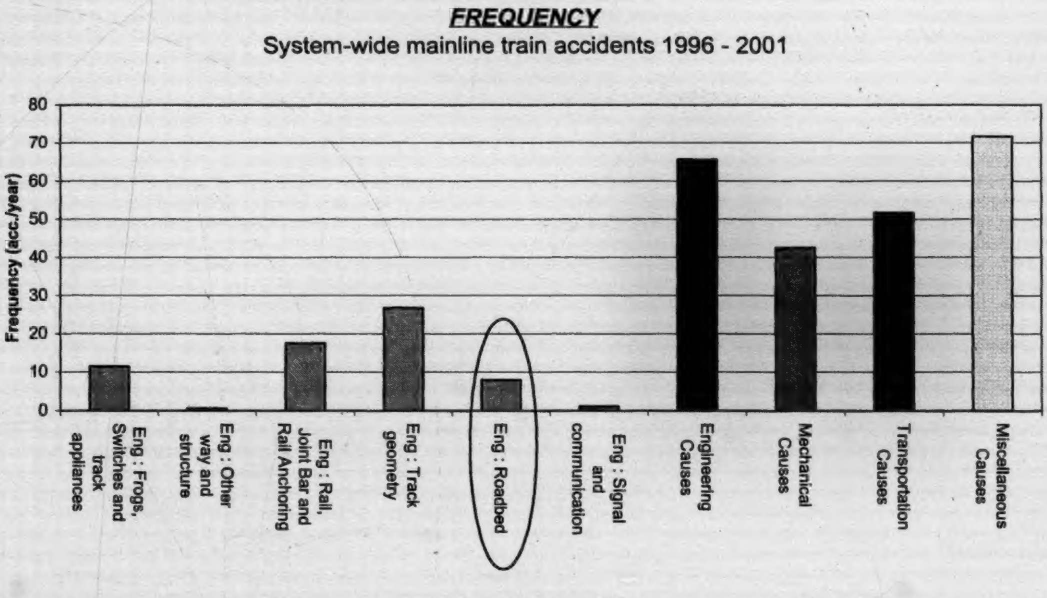


Figure 3-1 Frequency of train accident causes 1996 to 2001 from C.A.R.E.S.

Using the same format as Figure 3-1, Figure 3-2 presents the average severity of train accidents between 1996 and 2001 in terms of direct costs per accident. In this case Eng. Roadbed causes have the highest severity averaging close to $400,000 per accident.

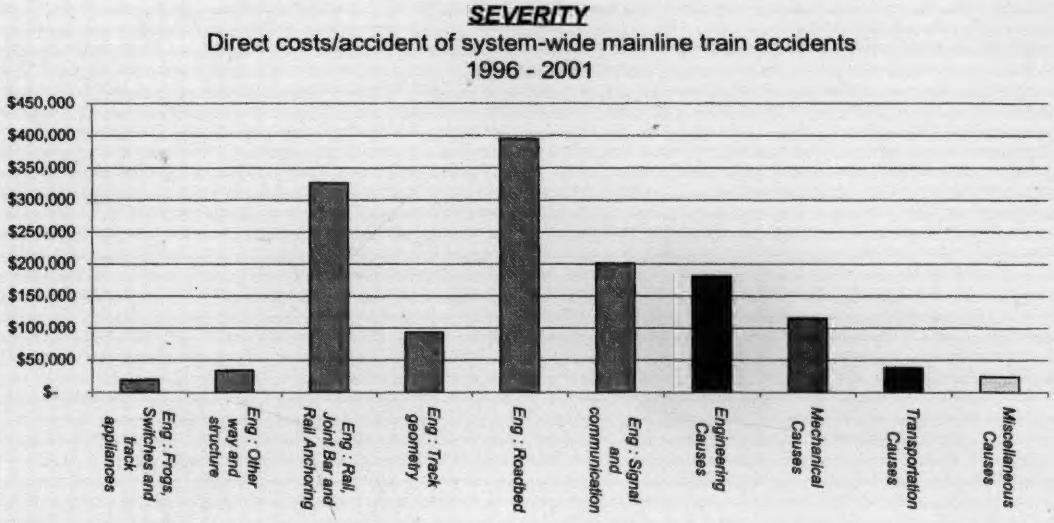


Figure 3-2 Severity of train accident causes 1996 to 2001 from C.A.R.E.S.

Figure 3-3 presents the total annual cost of train accidents between 1996 and 2001 in terms of direct costs per year. As this is the product of frequency and severity this chart is indicative of the risk associated with train accidents from the various causes at least over the 5 year record. Figure 3-3 indicates that for the 1996-2001 time period, *Eng. Roadbed* causes or ground hazards were the third highest annual direct cost and suggest that ground hazards are the third highest risk of train accidents. The reader is cautioned that this relatively short record period and, relative to other railway hazards, ground hazard incidents are influenced significantly by annual climatic conditions. Nonetheless it can be stated that ground hazards represent a relatively significant risk to railway operations.

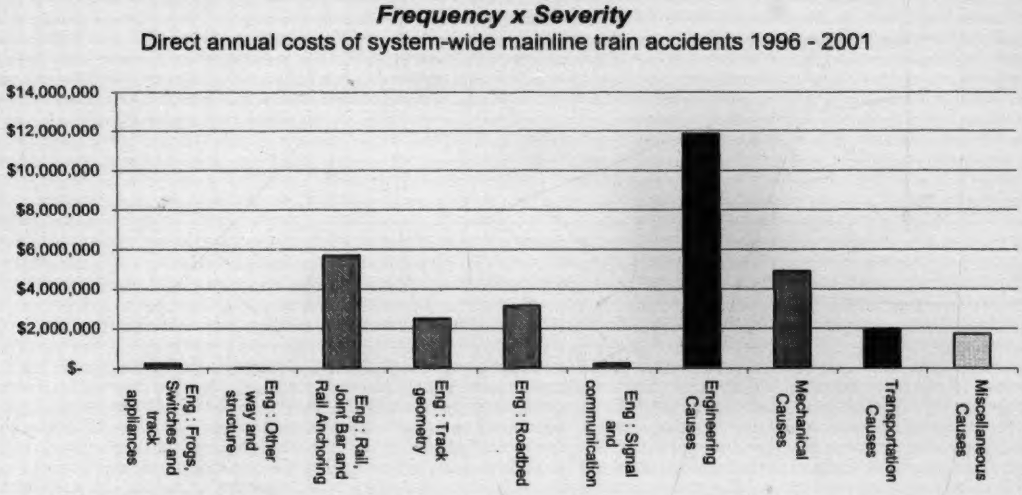


Figure 3-3 Direct annual costs (frequency x loss) of train accident causes 1996 to 2001 from C.A.R.E.S.

The last comparison of railway ground hazards to other railway hazards involves the track service outage resulting from a train accident from the variety of causes. Figure 3-4 presents the average outage times per incident for incidents that resulted in duration of one day or more. A minimum one-day duration was used for two reasons. Firstly, the *back in service time* field for outages less than 24 hours was rarely filled in so the information is not available. Secondly, studies have shown that revenue costs associated with a track service disruption are minimal in the first 24 hours, after which they tend to escalate dramatically (CNR, 1996) and are thus more relevant to this comparison than the outages of less than one day. The results indicate that outages resulting from ground hazards are proportionally longer than all other causes.

To summarize, it is evident that compared to other railway hazards, ground hazard caused train accidents are low in frequency ranking seventh, but have the highest severity or consequence of all hazards. This results in a third place ranking in terms of annual direct costs from train accidents. Finally the service disruptions resulting from railway ground hazard train accidents are proportionally higher than from any other cause and thus have the highest impact on track service disruption.

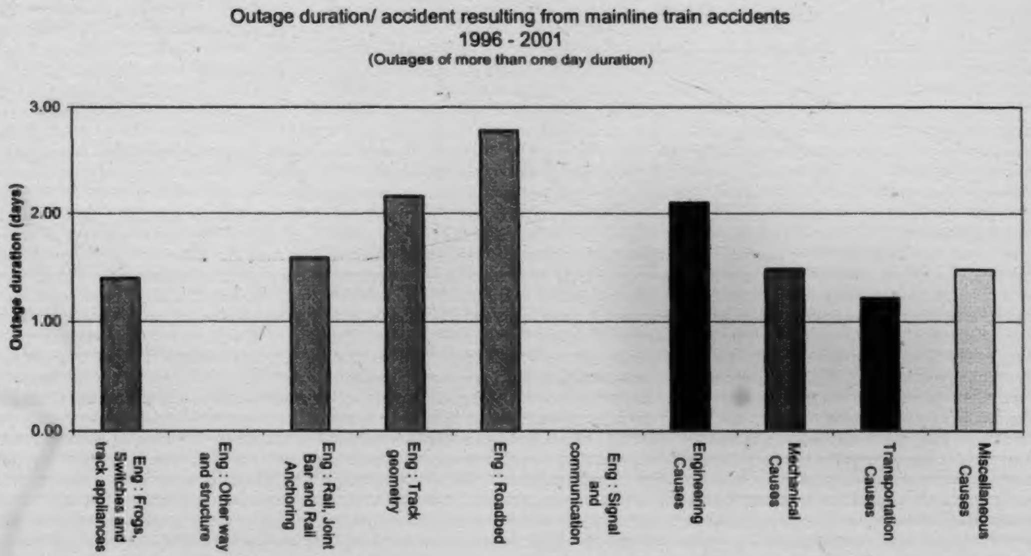


Figure 3-4 Outage duration resulting from mainline train accident causes 1996 to 2001 from C.A.R.E.S.

3.4 Railway Ground Hazard Event Analysis

The intent of this section is to analyze the available event record for CN in Canada in terms of frequency and severity of loss stemming from railway ground hazards. Only incidents affecting mainline track were considered in the analysis meaning minor ground hazard incidents in yards and spur tracks were excluded. A railway ground hazard event is defined as an incident stemming from a railway ground hazard that results in loss to the railway. From Chapter 2 the railway loss types include injury and fatality, train accidents and cleanup, train service disruption, and hazard mitigation. A spreadsheet of railway ground hazard event records was compiled using the following sources as described in Section 4.2:

- Train accident records from the CN's C.A.R.E.S. database
- CN Geotechnical files (Incident and mitigation records)

Mitigations, interventions to control or reduce the hazard, are considered events because they represent a loss in dollars as the result of a ground hazard. As well, in the majority of cases the mitigation was in response to a ground hazard that was assessed as being at or near failure.

The information for each record was sorted into the following categories:

1) Location Data
2) Temporal Data
3) Ground Hazard Data
4) Accident Data
5) Consequence Data
6) Risk Control Data
7) Source data

The spreadsheet entitled Ground Hazard Event Inventory has 963 records and is provided in an Excel © workbook entitled "Ground Hazards-Hazard event Working copy 1992-2003.xls" available through Appendix A. The database is broken down into three subsets based on both the timeframe and the location of the complete set of records as follows:

Subset 1. The train accident from road bed causes records from CARES (2001) are from 1992 to 2002 and contain records from all of Canada. (385 records)

Subset 2. The CN Geotechnical incident records represent major service disruptions from 1992 to 2002 and contain records from Western Canada only. Western Canada includes CN's operations from Northern Ontario to the Pacific coast. When these records are coincident with a CARES train accident record they are counted as a Subset 2 record. (38 records)

Subset 3. The CN geotechnical mitigation records are from 1982 to 2003 and contain records for the Jasper, Alberta to Vancouver, BC corridor from 1982 to 1995 and for Western Canada from 1996 to 2003. (540 records)

When these subsets are combined, the location and period that contains the most complete set of records is the corridor from Jasper, Alberta to Vancouver, BC between 1996 and 2002. Each record/event was classified according to Level III of the classification system and the records were edited to remove duplicate and redundant records. The following sections analyze this database in terms of ground hazard type and location. Only the appropriate subset(s) is used in each analysis. None of the costs were adjusted for inflation, as inflation in this time period was relatively flat at less than 3% per annum.

3.4.1 Loss Analysis by Railway Ground Hazard Type

Using the classification system presented in Chapter 2 the railway ground hazard events are first analyzed according to the level II and III classification and sorted according to ground hazard type. The ground hazard that is attributed to the event is the ultimate ground hazard that resulted in the railway loss. In many cases the ground hazard was complex which means a preceding hazard event resulted in the preparatory cause for the event that caused the railway loss. Complex ground hazard incident records are reviewed in Section 3.4.4. Table 3-3 presents a summary of the results for Subsets 1 and 2 of the database.

Table 3-3 Summary of losses from ground hazard caused main line train accidents CN Canada wide 1992-2002

Ground Hazard Causes		Train Accidents: CN Canada Wide (1992-2002) from C.A.R.E.S.						
Level II Categories	Level III Categories	Events	Injuries	Fatalities	Direct Costs	Frequency (events/year)	Severity (cost/ event)	Annual Cost (cost/year)
Landslides	Rock landslide	26	1	0	$ 1,634,589	2.4	$ 62,869	$ 148,599
	Debris landslide	13	2	0	$ 2,193,985	1.2	$ 168,768	$ 199,453
	Earth landslide	35	4	4	$ 24,428,539	3.2	$ 697,958	$ 2,220,776
Subsidence	Settlement	15	0	0	$ 423,953	1.4	$ 28,264	$ 38,541
	Collapse	1	0	0	$ 2,390	0.1	$ 2,390	$ 217
Hydraulic erosion	Overland flow	12	0	0	$ 4,972,233	1.1	$ 414,353	$ 452,021
	Through flow	4	3	0	$ 3,604,468	0.4	$ 901,117	$ 327,679
	Sub aqueous flow	0	0	0	$ -	0.0		$ -
Ice & snow	Snow avalanche	1	0	0	$ 79,459	0.1	$ 79,459	$ 7,224
	Frost heave	12	0	0	$ 42,204	1.1	$ 3,517	$ 3,837
	Icing	305	0	0	$ 468,111	27.7	$ 1,535	$ 42,556
	Total	**424**	**10**	**4**	**$ 37,849,931**	**38.55**	**$ 89,269**	**$ 3,440,903**

Figure 3-5 depicts the diversity in the frequency of train accidents from the Level III ground hazards showing icing to have the highest frequency. A review of the icing records reveals that the majority of these incidents are in Eastern Canada and are the result of ice build-up in road crossings or at switches and the derailments are relatively minor as shown by the low severity cost. An undeterminable number of these are the result of ice accumulation from groundwater discharge either from the uphill slope, a tunnel wall or roof or up from the track subgrade. The second highest frequency is attributed to earth landslide events followed by rock landslide events.

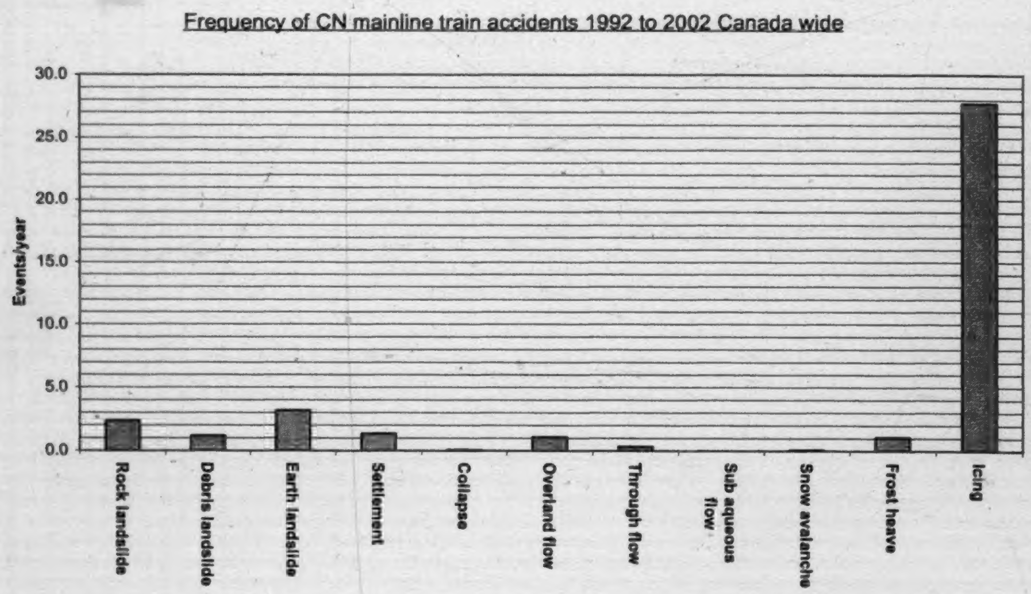


Figure 3-5 Frequency of CN mainline train accidents from ground hazards 1992 to 2002 Canada wide from Subset 1 and 2 of the database C.A.R.E.S.

In terms of severity, which is measured in units of direct cost resulting from the ground hazard caused incident, Figure 3-6 indicates that throughflow hazards have had the highest severity followed by earth landslides, overland flow, debris landslides, snow avalanche, rock landslides and through flow in that order. Note that these results may be misleading as there are only four records of through flow and only one record of snow avalanche.

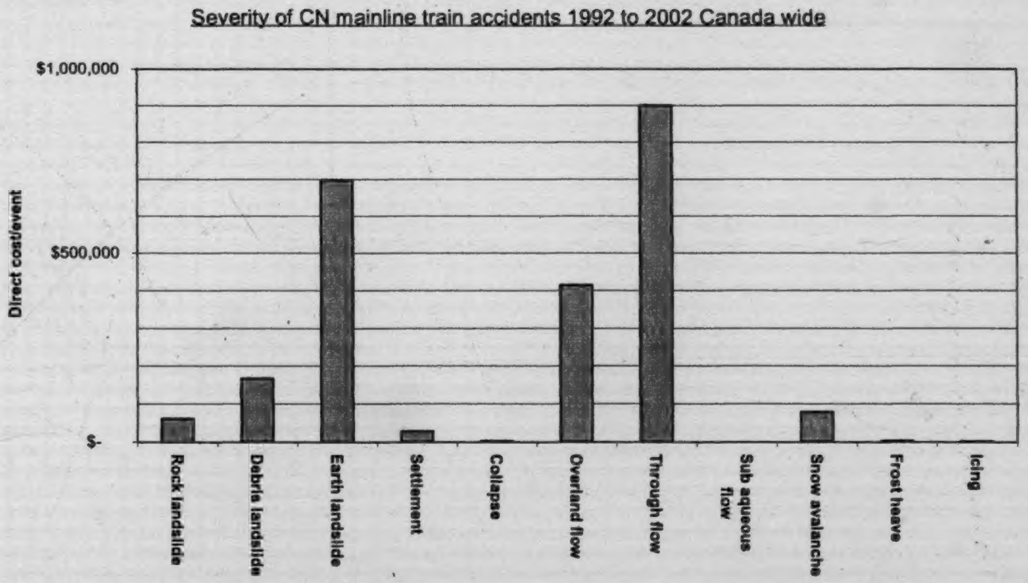


Figure 3-6 Severity in direct costs per event of CN mainline train accidents from Level III ground hazards 1992 to 2002 Canada wide from Subset 1 of the database C.A.R.E.S.

Finally Figure 3-7 presents the annual costs from Subsets 1 and 2 attributed to each level III ground hazard. This is indicative of the risk of train accident and major service disruption direct costs from the 1992 to 2002 time frame associated with railway ground hazards. Using the same information Figure 3-8 depicts the proportion of direct costs attributed to each level III ground hazard. Of all the level III ground hazards, clearly earth landslides have had the dominant impact in terms of annual direct costs. Also of relative significance are overland flow, through flow, debris landslides and rock landslides. Note that CN has maintained ongoing hazard management systems and stabilization programs for rockfall, snow avalanche and gullying hazards through this time frame and these have no doubt reduced the annual costs resulting from these hazard events. Namely these systems include:

- CN Rockfall Hazard and Risk Assessment (CNRHRA) System
- Snow Avalanche Assessment and Management System
- CN Beaver Activity Hazard Assessment (BAHA) System

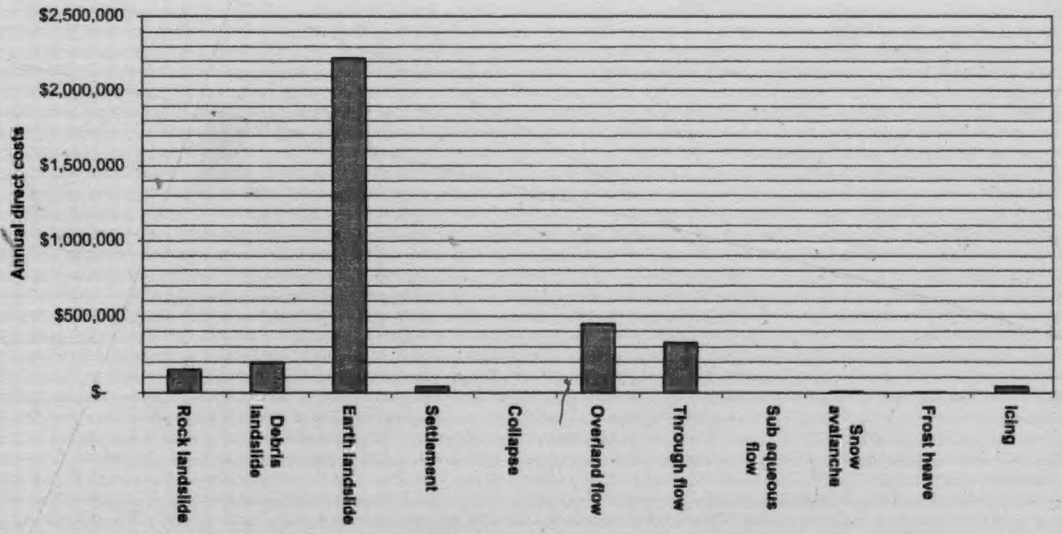


Figure 3-7 Annual direct costs of CN mainline train accidents in Canada for Level III ground hazards 1992 to 2002 from Subset 1 of the C.A.R.E.S. database

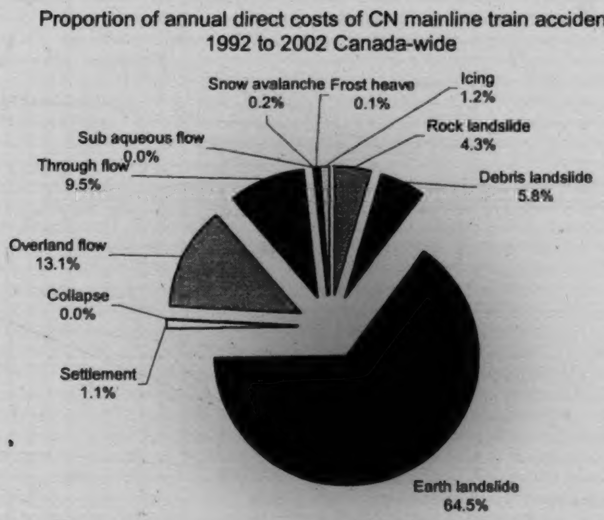


Figure 3-8 Proportion of annual direct costs of CN mainline train accidents from Level III ground hazards 1992 to 2002 Canada-wide from Subset 1 of the database C.A.R.E.S.

3.4.2 Trend Analysis of Railway Ground Hazard events 1992-2002

Figure 3-9 shows a combined plot of frequency, severity and annual costs attributed to ground hazards from Subset 1. Although this plot shows an apparent decline in the frequency of ground hazard events it also shows a significant fluctuation in annual costs per year. From the author's experience, this fluctuation is mainly due to significant variation in climatic conditions namely rainfall intensity and duration; snow pack at high, medium and low elevations and freeze thaw conditions. Given this fluctuation and the relatively short time frame of ten years, the downward trend in occurrence frequency is likely not a reliable indicator of the future.

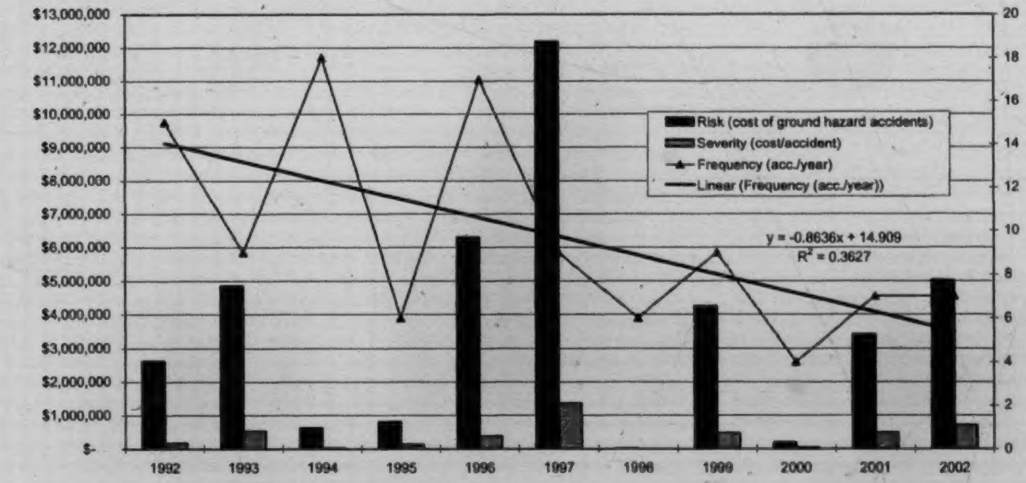
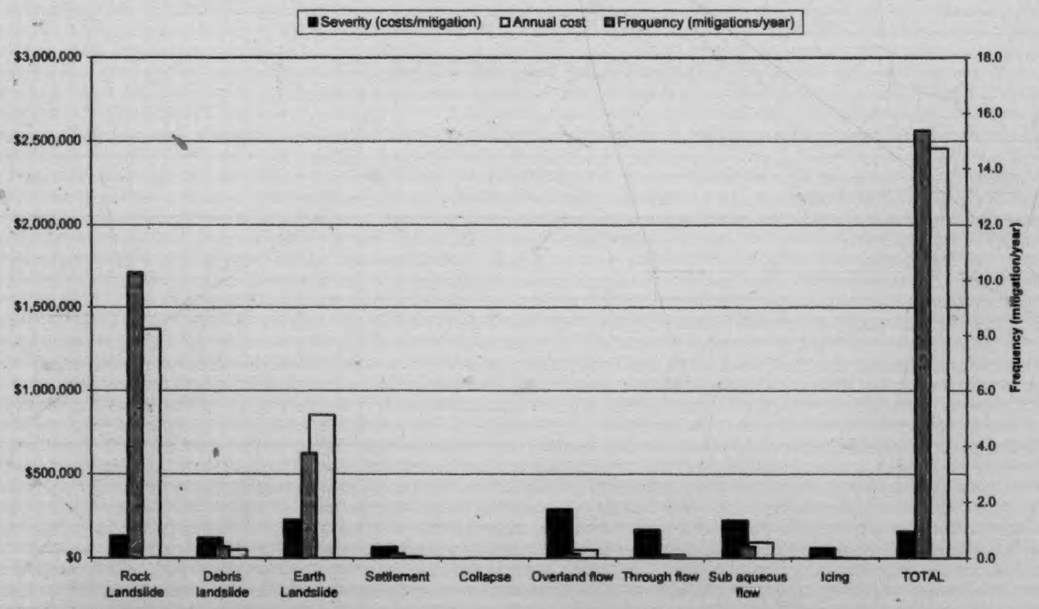


Figure 3-9 Combined Chart: Annual Loss (cost per year), Severity (cost per incident) and Frequency (incidents per year) attributed to Ground Hazards 1992 to 2002

3.4.3 Loss Analysis by Railway Ground Hazard Mitigation

Planned or unplanned mitigation of railway ground hazards is considered a loss attributable to railway ground hazards and thus must be assessed as part of the total risk. A complete record of mitigation on CN from 1980 to 2003 is only available for the Jasper, Alberta to Vancouver, BC corridor. **Figure 3-10** presents a summary of these records according to the ground hazard event type. These records are included in Appendix III.

Apparent from Figure 3-10, the largest component of mitigation effort has been expended on rock fall hazards from 1980 to 2003. This aggressive program of rock stabilization actually started in the early 1970's following the fatal derailment at Boothroyd Mile 119 of the Ashcroft Subdivision in 1972. This program is likely the reason that rock fall events are relatively low compared to earth slides and others as shown in Figure 3-7.



Ground Hazard Level III Classification	# mitigation records	Cost of mitigation	Frequency (mitigations/year)	Severity (costs/mitigation)	Annual cost
Rock Landslide	247	$ 32,958,063	10.3	$ 133,433	$ 1,373,253
Debris landslide	10	$ 1,223,500	0.4	$ 122,350	$ 50,979
Earth Landslide	90	$ 20,450,541	3.8	$ 227,228	$ 852,106
Settlement	4	$ 270,000	0.2	$ 67,500	$ 11,250
Collapse	0	$ -	0.0		$ -
Overland flow	4	$ 1,165,000	0.2	$ 291,250	$ 48,542
Through flow	3	$ 509,000	0.1	$ 169,667	$ 21,208
Sub aqueous flow	10	$ 2,259,766	0.4	$ 225,977	$ 94,157
Icing	1	$ 60,000	0.0	$ 60,000	$ 2,500
TOTAL	**369**	**$ 58,895,870**	**15.4**	**$ 159,609**	**$ 2,453,995**

Figure 3-10 Summary of Ground Hazard mitigation for the Jasper to Vancouver corridor 1980 to 2003 by Ground Hazard type.

In addition to these costs, CN has maintained a snow avalanche management program on the Bulkley and Skeena Subdivisions at the western end of the Tete Jaune to Prince

Rupert Corridor since the early 1970's and on the Albreda and Robson Subdivisions on the east end of the Jasper to Vancouver Corridor. Following ongoing hazard assessments in the winter months, mitigation would include triggering high potential avalanches with explosives from either artillery guns, dropped from helicopter or placed from the ground. The costs for this work averaged $10,000 per mitigation, averaging 16 mitigations per year amounting to approximately $160,000 per year.

3.4.4 Losses from Complex Ground Hazards

Complex ground hazards are hazards that involve more than one type of railway ground hazard in sequence and are named to describe the chain of events or risk scenario that may ultimately result in track failure. To capture these types of hazards from the loss records additional fields for any preceding hazard event were added to the spread sheet and care was taken to populate these fields if a preceding ground hazard event had occurred. The database was then queried for different combinations of known complex railway ground hazards. presents a summary of all complex railway ground hazards contained in subset 1 and 2 of the event records. It is apparent that a significant proportion, 63%, of the annual costs from ground hazard events involves complex ground hazards. The most significant events are those that ultimately resulted in an earth landslide. The most significant complex ground hazard event was the earth slide-earth flow event that occurred at Conrad siding at Mile 106.14, Ashcroft Subdivision in March of 1997.

Level III Classification	Complex ground hazard	# of records	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual cost	Proportion of complex ground hazard to total in Level III Class
Rock Landslide	Rock landslide-Rock Landslide	1	$ 250,000	0.09	$ 250,000	$ 22,727	15%
	Complex Rock Landslide total	***1***	***$ 250,000***	***0.09***	***$ 250,000***	***$ 22,727***	***15%***
Rock Landslide	***All Rock Landslide total***	**26**	**$ 1,634,589**	**2.36**	**$ 62,869**	**$ 148,599**	**100%**
Debris Landslide	Rock Landslide-Debris landslide	1	$ 29,480	0.09	$ 29,480	$ 2,680	1%
	Complex Debris Landslide total	***1***	***$ 29,480***	***0.09***	***$ 29,480***	***$ 2,680***	***1%***
Debris Landslide	***All Debris Landslide total***	**13**	**$ 2,193,985**	**1.18**	**$ 168,768**	**$ 199,453**	**100%**
Earth Landslide	Debris Landslide-Earth Landslide	1	$ 2,000,000	0.09	$ 2,000,000	$ 181,818	8%
Earth Landslide	Earth Landslide-Earth Landslide	2	$ 13,000,000	0.18	$ 6,500,000	$ 1,181,818	52%
Earth Landslide	Subsidence-Earth Landslide	1	$ 150,000	0.09	$ 150,000	$ 13,636	1%
Earth Landslide	Overland flow-Earth Landslide	3	$ 2,045,000	0.27	$ 681,667	$ 185,909	8%
Earth Landslide	Through flow-Earth Landslide	1	$ 10,000	0.09	$ 10,000	$ 909	0%
Earth Landslide	Sub aqueous Flow-Earth Landslide	10	$ 2,204,000	0.91	$ 220,400	$ 200,364	9%
	Complex Earth Landslide total	***18***	***$ 19,409,000***	***1.64***	***$ 1,078,278***	***$ 1,764,455***	***78%***
Earth Landslide	***All Earth Landslides total***	**37**	**$ 24,788,539**	**3.36**	**$ 669,961**	**$ 2,253,504**	**100%**
Overland flow	Debris landslide-Overland flow	1	$ 50,000	0.09	$ 50,000	$ 4,545	1%
Overland flow	Sub aqueous Flow-Overland flow	1	$ 50,000	0.09	$ 50,000	$ 4,545	1%
	Complex Overland Flow total	***2***	***$ 100,000***	***0.18***	***$ 50,000***	***$ 9,091***	***2%***
Overland flow	***All Overland Flow total***	**13**	**$ 5,022,233**	**1.18**	**$ 386,326**	**$ 456,567**	**100%**
Through flow	Collapse-Through flow	1	$ 3,500,000	0.09	$ 3,500,000	$ 318,182	97%
	Complex Through flow total	***1***	***$ 3,500,000***	***0.09***	***$ 3,500,000***	***$ 318,182***	***97%***
Through flow	***All Through flow total***	**4**	**$ 3,604,468**	**0.36**	**$ 901,117**	**$ 327,679**	**100%**
Complex Ground Hazards total		***23***	***$ 23,288,480***	***2.09***	***$ 1,012,543***	***$ 2,117,135***	***63%***
All Ground Hazards total		***93***	***$ 37,243,814***	***8.45***	***$ 400,471***	***$ 3,385,801***	***100%***

Table 3-4 Summary and comparison of Railway Complex Ground Hazard caused events to all ground hazard caused events in CN Western Canada 1992 to 2002

The next step in these analyses of the Level III ground hazards is to examine and correlate the occurrence locations of the more prevalent ground hazard events.

3.4.5 Loss Analysis by Railway Ground Hazard Location

Using the classification system presented in Chapter 2 the railway ground hazard events are sorted by location according to the level III classification. Once again the ground hazard that ultimately resulted in the railway loss is attributed to the event. This exercise utilizes Subsets 1 and 2 of the database that comprises 1992 to 2002 for CN's West Canada Region (see Figure 3-11). Note that event records for BC Rail which became part of CN in 2005 are not included in this analysis. Recall that subset 2 contains significant events that resulted in either long outages and/or high costs but not necessarily a train accident. The costs reported for these events are the direct costs including property loss and cost to restore service.

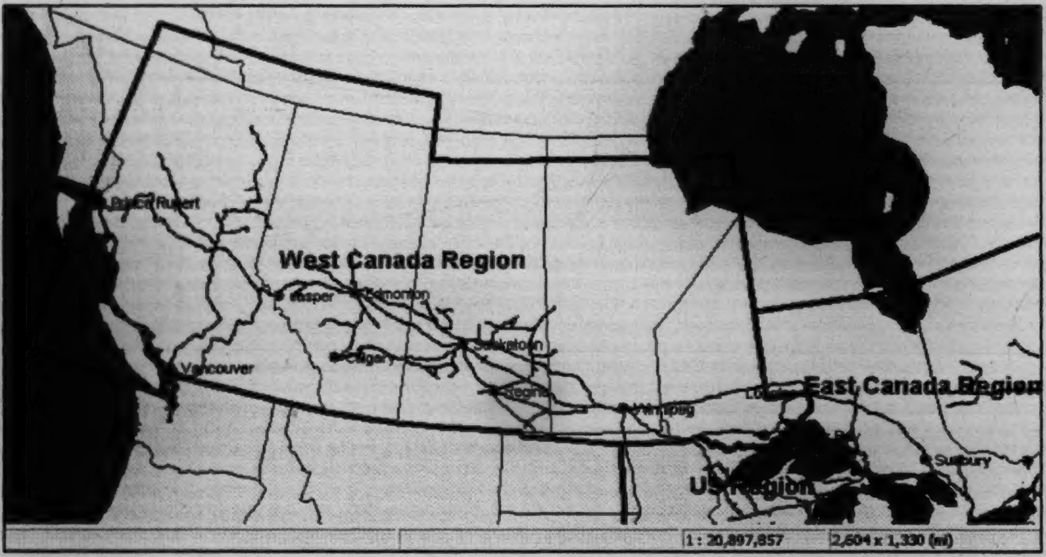

Prince Rupert
West Canada Region
Jasper
Edmonton
Saskatoon
Calgary
Vancouver
Regina
Winnipeg
East Canada Region
Sudbury
US Region
1 : 20,897,857
2,604 x 1,330 (mi)

Figure 3-11 Map of CN West Canada Region (from CN GIS, 2004)

Table 3-5 presents a summary of the reported direct losses contained in subsets 1 and 2 in terms of frequency, severity and annual costs.

Figure 3-12 presents the same results in a graphical format. It is obvious from

Figure **3-12** that the Edmonton to Vancouver corridor is the most affected by ground hazards in Western Canada in the 1992 to 2002 timeframe. This result is not all that surprising given the high density of train traffic, the high relief, the density and diversity of natural hazards and the relative youth of the terrain and river systems. Table 3-6 presents a further breakdown of these results into the specific CN subdivisions.

Table 3-5 Location summary by corridor of Ground Hazard events for CN Western Canada 1992 to 2002

Corridor	# of events	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	11	$ 548,135	1.00	$ 49,830	$ 49,830
Longlac, Ontario to Winnipeg	15	$ 8,342,792	1.36	$ 556,186	$ 758,436
Winnipeg to Edmonton Southline	13	$ 90,770	1.18	$ 6,982	$ 8,252
Winnipeg to Edmonton Northline	1	$ 450	0.09	$ 450	$ 41
Saskatoon to Calgary	5	$ 1,373,025	0.45	$ 277,378	$ 124,820
Edmonton to Calgary	6	$ 967	0.55	$ 161	$ 88
Edson to Mountain Park, Alberta	0	$ -	0.00	$ -	$ -
Edmonton to Vancouver	57	$ 22,358,858	5.18	$ 392,261	$ 2,032,623
Tete Jaune, BC to Prince Rupert, BC	18	$ 948,837	1.64	$ 52,713	$ 86,258
Western Canada Total	126	$ 33,663,834	11.45	$ 267,173	$ 3,060,349

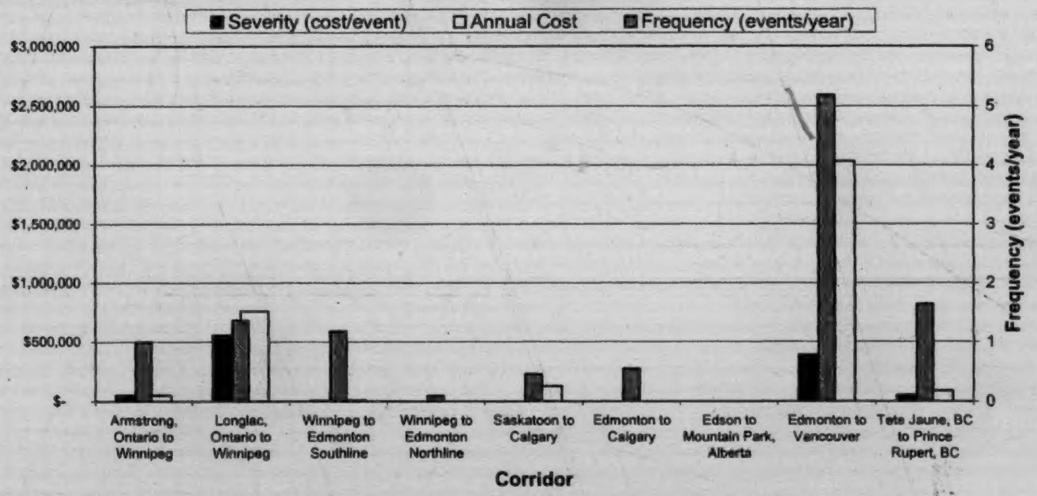


Figure 3-12 Location summary by corridor of ground hazard events by frequency, severity and annual costs for Western Canada, 1992 to 2002

Table 3-6 Location summary by CN subdivision of Ground Hazard events in Western Canada 1992 to 2002

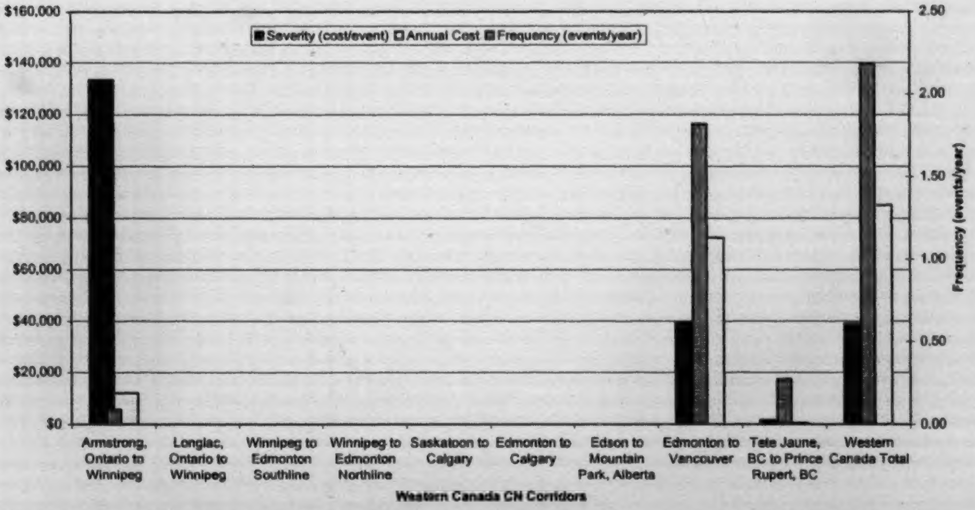
Corridor	Subdivision	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	Allanwater	0.09	$ -	$ -
	Redditt	0.91	$ 55,814	$ 50,740
	Corridor Total	**1.00**	**$ 50,740**	**$ 50,740**
Longlac, Ontario to Winnipeg	Kinghorn	0.18	$ 1,750,002	$ 318,182
	Kashabowie	0.36	$ 467	$ 170
	Fort Frances	0.73	$ 604,716	$ 439,793
	Sprague	0.09	$ 3,195	$ 290
	Corridor Total	**1.36**	**$ 556,186**	**$ 758,436**
Winnipeg to Edmonton Southline	Rivers	0.55	$ 1,964	$ 1,071
	Watrous	0.36	$ 717	$ 261
	Wainwright	0.27	$ 25,374	$ 6,920
	Corridor Total	**1.18**	**$ 6,982**	**$ 8,252**
Winnipeg to Edmonton Northline	Gladstone	0.00		$ -
	Togo	0.00		$ -
	Margo	0.00		$ -
	Aberdeen	0.00		$ -
	Blackfoot	0.00		$ -
	Vegreville	0.09	$ 450	$ 41
	Corridor Total	**0.09**	**$ 450**	**$ 41**
Saskatoon to Calgary	Rosetown	0.00		$ -
	Conquest	0.00		$ -
	Elrose	0.00		$ -
	Oyen	0.18	$ 425	$ 77
	Drumheller	0.27	$ 457,392	$ 124,743
	Corridor Total	**0.45**	**$ 274,605**	**$ 124,820**
Edmonton to Calgary	Camrose	0.09	$ -	$ -
	Brazeau	0.36	$ 242	$ 88
	Strachan	0.00		$ -
	Ram River	0.09	$ -	$ -
	Three Hills	0.00		$ -
	Corridor Total	**0.55**	**$ 161**	**$ 88**
Edson to Mountain Park, Alberta	Foothills	0.00		$ -
	Mountain Park	0.00		$ -
	Luscar Industrial	0.00		$ -
	Corridor Total	**0.00**	**$ -**	**$ -**
Edmonton to Vancouver	Edson	0.36	$ 490,611	$ 178,404
	Albreda	1.27	$ 62,958	$ 80,129
	Robson	0.36	$ 852,230	$ 309,902
	Clearwater	0.45	$ 112,915	$ 51,325
	Ashcroft	1.82	$ 716,928	$ 1,303,505
	Yale	0.91	$ 120,295	$ 109,359
	Corridor Total	**5.18**	**$ 392,261**	**$ 2,032,623**
Tete Jaune, BC to Prince Rupert, BC	Tete Jaune	0.00		$ -
	Fraser	0.73	$ 69,167	$ 50,303
	Nechako	0.18	$ 30,000	$ 5,455
	Telkwa	0.00		$ -
	Bulkley	0.18	$ 10,250	$ 1,864
	Skeena	0.55	$ 77,500	$ 42,273
	Kitimat	0.00		$ -
	Corridor Total	**1.64**	**$ 61,047**	**$ 99,894**
Western Canada Total		**11.45**	**$ 268,443**	**$ 3,074,894**

From **Table 3-6** it is apparent that the Ashcroft Subdivision on the Edmonton to Vancouver corridor was the most difficult track section between 1992 and 2002. In fact the annual costs on the Ashcroft are more than four times higher than on any other subdivision. This is due in part to the tragic derailment and fatalities resulting from an earth slide-earth flow event that occurred in March 1997 at Mile 106.14 of the Ashcroft subdivision. The direct costs form this derailment alone were in the order of $12M.

In the following sections each Level III ground hazard type is broken out by location to assess the regional distribution of the ground hazard type.

3.4.5.1 Rock Landslides by Location

The table and chart presented in Figure 3-1 shows the distribution of rock landslide losses in Western Canada between 1992 and 2002. As expected the majority of the incidents coincide with the mountainous high tonnage corridor between Edmonton and Vancouver.

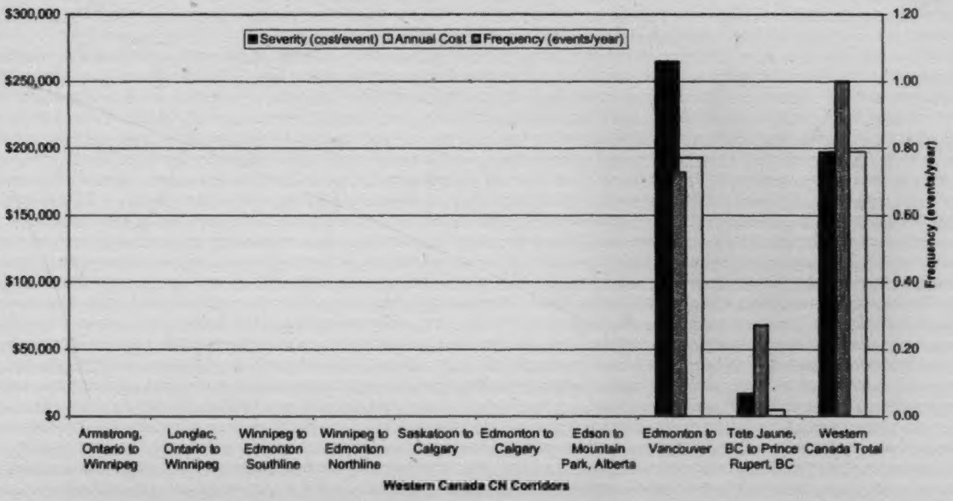


Corridor	# of events	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	1	$ 133,476	0.09	$ 133,476	$ 12,134
Longlac, Ontario to Winnipeg	0	$ -	0.00		$ -
Winnipeg to Edmonton Southline	0	$ -	0.00		$ -
Winnipeg to Edmonton Northline	0	$ -	0.00		$ -
Saskatoon to Calgary	0	$ -	0.00		$ -
Edmonton to Calgary	0	$ -	0.00		$ -
Edson to Mountain Park, Alberta	0	$ -	0.00		$ -
Edmonton to Vancouver	20	$ 797,184	1.82	$ 39,859	$ 72,471
Tete Jaune, BC to Prince Rupert, BC	3	$ 5,000	0.27	$ 1,667	$ 455
Western Canada Total	24	$ 935,660	2.18	$ 38,986	$ 85,060

Figure 3-13 Division of rock landslide caused incidents in Western Canada from 1992 to 2002 by corridor.

3.4.5.2 Debris Landslides by Location

Figure 3-14 shows that for this period debris flow events primarily affect the Edmonton to Vancouver and Tete Jaune to Prince Rupert corridors. This is not surprising as these are the two main corridors where the track passes through mountainous terrain. These events were primarily the result of channelized debris flows. Not shown here are events where debris flows were the penultimate event that led to a different ground hazard, From debris flows preceeded 8% of the earth landslide events and 1% of the overland flow events.

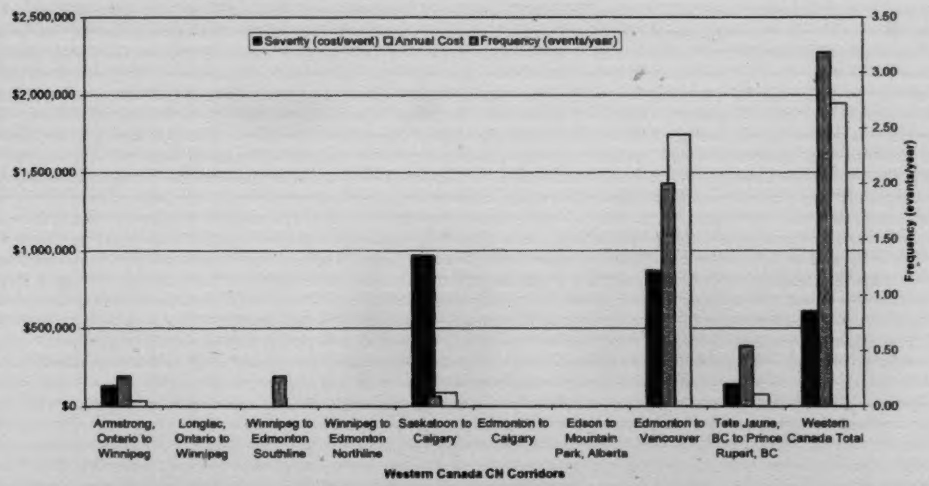


Corridor	# of events	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	0	$ -	0.00		$ -
Longlac, Ontario to Winnipeg	0	$ -	0.00		$ -
Winnipeg to Edmonton Southline	0	$ -	0.00		$ -
Winnipeg to Edmonton Northline	0	$ -	0.00		$ -
Saskatoon to Calgary	0	$ -	0.00		$ -
Edmonton to Calgary	0	$ -	0.00		$ -
Edson to Mountain Park, Alberta	0	$ -	0.00		$ -
Edmonton to Vancouver	8	$ 2,117,485	0.73	$ 264,686	$ 192,499
Tete Jaune, BC to Prince Rupert, BC	3	$ 50,500	0.27	$ 16,833	$ 4,591
Western Canada Total	11	$ 2,167,985	1	$ 197,090	$ 197,090

Figure 3-14 Division of debris landslide caused incidents in Western Canada from 1992 to 2002 by corridor.

3.4.5.3 Earth Landslides by Location

Figure 3-15 illustrates the losses resulting from earth landslide events in the 1992 to 2002 time frame and again shows that the Edmonton to Vancouver corridor was the most difficult corridor by a significant margin. Based on the author's experience this is primarily due to the high relief, the close proximity of the track to major rivers, the youth of this terrain and river system, and the abundance of silty soils along this corridor. Similarly events on the Tete Jaune to Prince Rupert corridor seem to be related to their proximity to the river, moderate to high relief, and abundance of both weak clay and silty soils. In the prairie corridors earth slides are usually associated with post glacial river valleys particularly where the tracks decend or ascend the valley slopes.



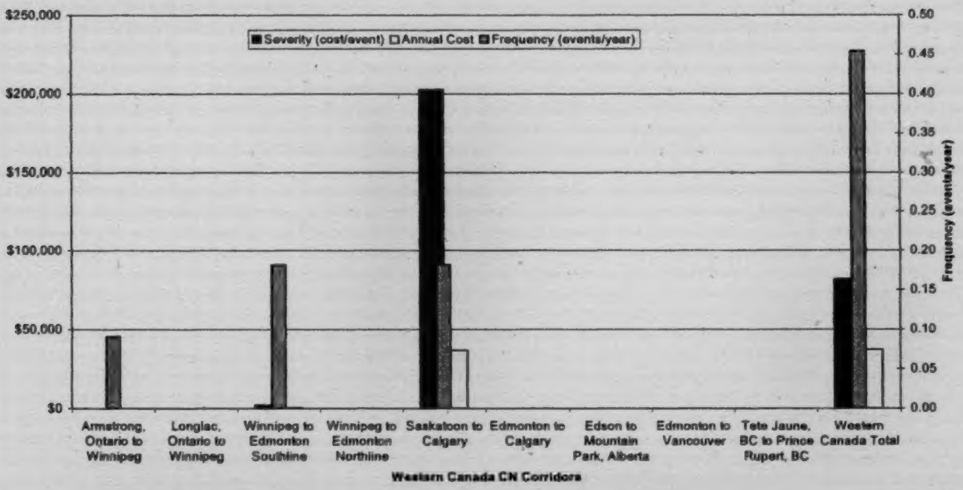
Corridor	# of events	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	3	$ 400,000	0.27	$ 133,333	$ 36,364
Longlac, Ontario to Winnipeg	0	$ -	0.00		
Winnipeg to Edmonton Southline	3	$ -	0.27	$ -	$ -
Winnipeg to Edmonton Northline	0	$ -	0.00		
Saskatoon to Calgary	1	$ 967,872	0.09	$ 967,872	$ 87,988
Edmonton to Calgary	0	$ -	0.00		
Edson to Mountain Park, Alberta	0	$ -	0.00		
Edmonton to Vancouver	22	$ 19,183,771	2.00	$ 871,990	$ 1,743,979
Tete Jaune, BC to Prince Rupert, BC	6	$ 860,000	0.55	$ 143,333	$ 78,182
Western Canada Total	35	$ 21,411,643	3.18	$ 611,761	$ 1,946,513

Figure 3-15 Division of earth landslide caused incidents in Western Canada from 1992 to 2002 by corridor.

Earth slides that occur on corridors that traverse, on to the Canadian Shield, primarily in Northern Ontario, occur most commonly at transitions from weak soils to bedrock due to sloping bedrock surfaces, concentrated seepage paths and weak clay and organic soils.

3.4.5.4 Settlement by Location

From Figure 3-16, settlement, defined as a slow process of vertical displacement of the track, is more prevalent in the Interior Plains presumably due to the abundance of weak clay subgrades and the lack of drainage in the very low relief area.



Corridor	# of events	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	1	$ -	0.09	$ -	$ -
Longlac, Ontario to Winnipeg	0	$ -	0.00		
Winnipeg to Edmonton Southline	2	$ 4,450	0.18	$ 2,225	$ 405
Winnipeg to Edmonton Northline	0	$ -	0.00		
Saskatoon to Calgary	2	$ 405,153	0.18	$ 202,577	$ 36,832
Edmonton to Calgary	0	$ -	0.00		
Edson to Mountain Park, Alberta	0	$ -	0.00		
Edmonton to Vancouver	0	$ -	0.00		
Tete Jaune, BC to Prince Rupert, BC	0	$ -	0.00		
Western Canada Total	5	$ 409,603	0.45	$ 81,921	$ 37,237

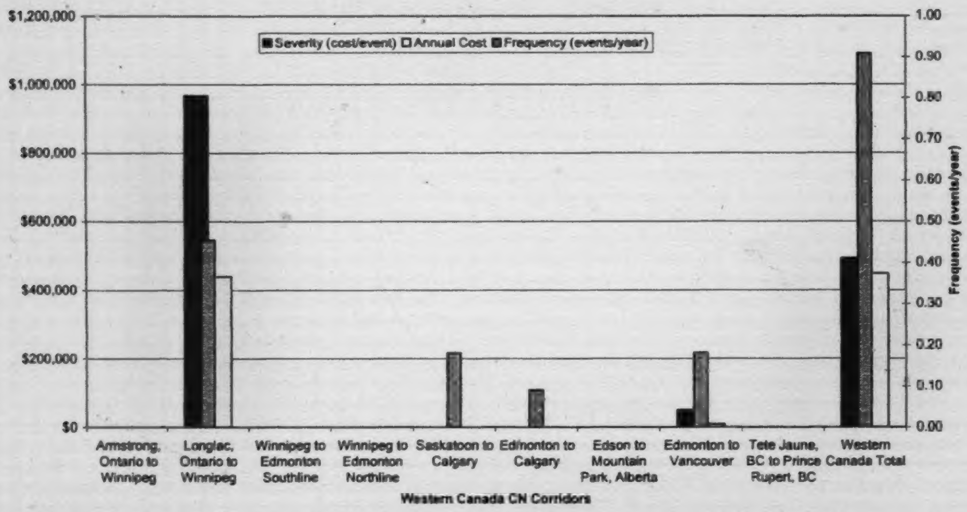
Figure 3-16 Division of settlement caused incidents in Western Canada from 1992 to 2002 by corridor.

3.4.5.5 Collapse by Location

There are no incidents in the 1992 to 2002 record where collapse was suspected to be the primary cause. However, a collapse was suspected as a preparatory cause in a complex collapse-through flow hazard event which resulted in a serious derailment and injuries in 1994 at Orient Bay on the Kinghorn derailment (TSB 1996). Nonetheless there have been numerous incidents of collapse holes discovered in the ballast section, that fortunately did not result in track structure d.

3.4.5.6 Overland Flow Erosion by Location

Overland flow erosion track failures are commonly called "washouts" by railway personnel. Overland flow erosion level IV hazards include slope wash and gullying erosion. As shown in Figure 3-17, the most difficult corridor in this time frame was the Longlac to Winnipeg corridor where the majority of the events were associated with intense rain storms. These hazards are made more severe by significant beaver activity in these areas. Beavers block drainage, in ditches and culverts, increase peak flows during flood due to dam breaches, increase the flood flow volume, increase stream bed erosion and contribute debris, primarily woody, to the flood flows.

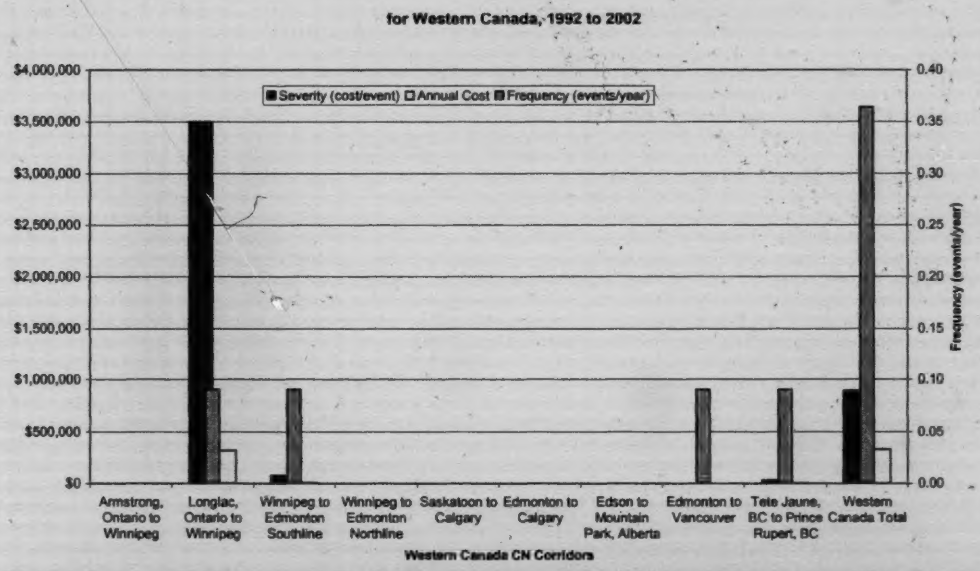


Corridor	# of events	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	0	$ -	0.00		
Longlac, Ontario to Winnipeg	5	$ 4,835,000	0.45	$ 967,000	$ 439,545
Winnipeg to Edmonton Southline	0	$ -	0.00		
Winnipeg to Edmonton Northline	0	$ -	0.00		
Saskatoon to Calgary	2	$ -	0.18	$ -	$ -
Edmonton to Calgary	1	$ -	0.09	$ -	$ -
Edson to Mountain Park, Alberta	0	$ -	0.00		
Edmonton to Vancouver	2	$ 100,000	0.18	$ 50,000	$ 9,091
Tete Jaune, BC to Prince Rupert, BC	0	$ -	0.00		
Western Canada Total	10	$ 4,935,000	0.91	$ 493,500	$ 448,636

Figure 3-17 Division of overland flow caused incidents in Western Canada from 1992 to 2002 by corridor.

3.4.5.7 Through Flow Erosion by Location

The through flow erosion caused events depicted in Figure 3-18 were primarily the result of seepage erosion and piping. The most significant event occurred on the Kinghorn Subdivision in the vicinity of Orient Bay in the Spring of 1994. The inferred cause of the grade failure in this case was essentially a piping failure brought on by a groundwater recharge following a seasonal snow melt (TSB, 1996).



Corridor	# of events	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	0	$ -	0.00		
Longlac, Ontario to Winnipeg	1	$ 3,500,000	0.09	$ 3,500,000	$ 318,182
Winnipeg to Edmonton Southline	1	$ 74,468	0.09	$ 74,468	$ 6,770
Winnipeg to Edmonton Northline	0	$ -	0.00		
Saskatoon to Calgary	0	$ -	0.00		
Edmonton to Calgary	0	$ -	0.00		
Edson to Mountain Park, Alberta	0	$ -	0.00		
Edmonton to Vancouver	1	$ -	0.09	$ -	$ -
Tete Jaune, BC to Prince Rupert, BC	1	$ 30,000	0.09	$ 30,000	$ 2,727
Western Canada Total	4	$ 3,604,468	0.36	$ 901,117	$ 327,679

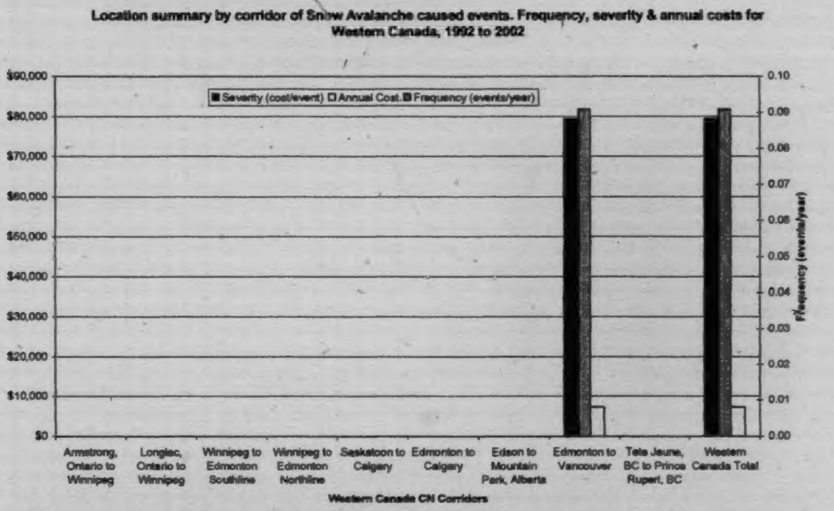
Figure 3-18 Division of through flow caused incidents in Western Canada from 1992 to 2002 by corridor.

3.4.5.8 Sub-aqueous Flow Erosion by Location

There are no reported sub-aqueous flow erosion directly caused incidents in the 1992 to 2002 record for Western Canada. In all cases in this time frame these hazardous events were detected in the early stages of erosion and the hazards mitigated. As shown in sub-aqueous flow erosion has contributed to a total of 10 incidents as the penultimate ground hazard event in a complex sub-aqueous-earth landslide event.

3.4.5.9 Snow Avalanche by Location

There is only one snow avalanche caused event in the record which occurred at Mile 4.4 of the Robson Subdivision in March of 1994.

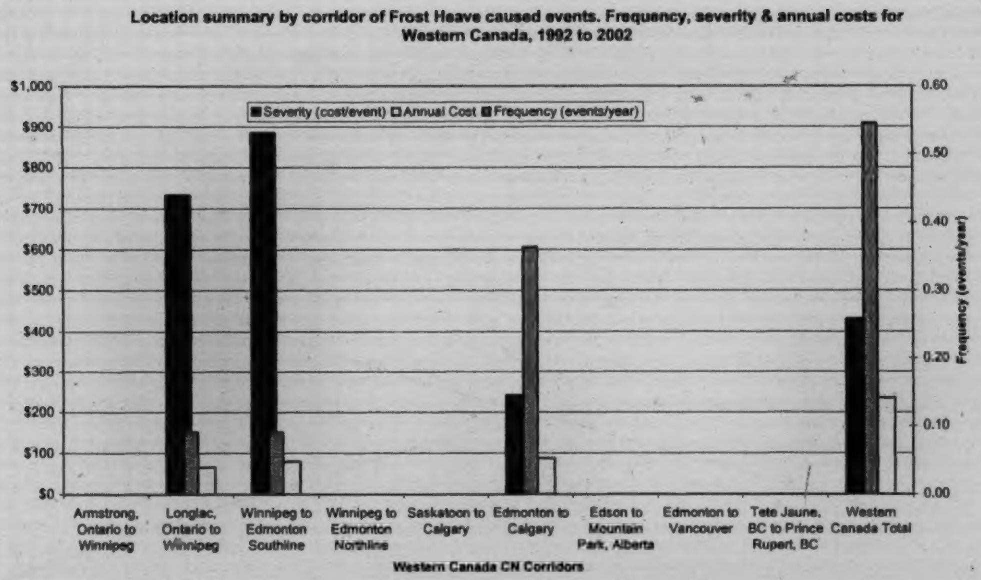


Corridor	# of events	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	0	$ -	0.00		
Longlac, Ontario to Winnipeg	0	$ -	0.00		
Winnipeg to Edmonton Southline	0	$ -	0.00		
Winnipeg to Edmonton Northline	0	$ -	0.00		
Saskatoon to Calgary	0	$ -	0.00		
Edmonton to Calgary	0	$ -	0.00		
Edson to Mountain Park, Alberta	0	$ -	0.00		
Edmonton to Vancouver	1	$ 79,459	0.09	$ 79,459	$ 7,224
Tete Jaune, BC to Prince Rupert, BC	0	$ -	0.00		
Western Canada Total	1	$ 79,459	0.09	$ 79,459	$ 7,224

Figure 3-19 Division of snow avalanche caused incidents in Western Canada from 1992 to 2002 by corridor.

3.4.5.10 Frost Heave by Location

As shown in Figure 3-20 incidents resulting from frost heaves have occurred in the Northern Ontario and Alberta corridors. They have been relatively infrequent and the severities have been relatively low.

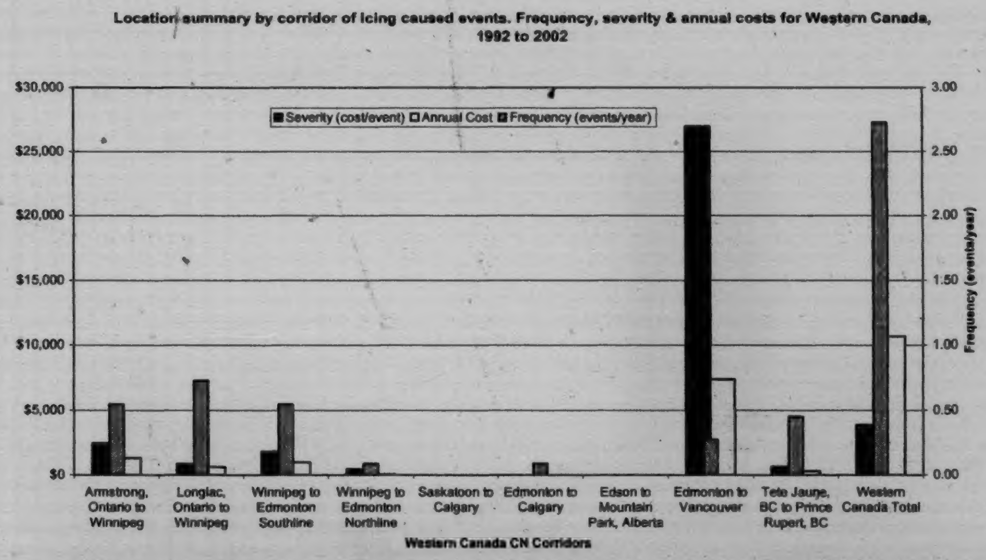


Corridor	# of events	Cost of events	Frequency (events/year)	Severity (cost/event)	Annual Cost
Armstrong, Ontario to Winnipeg	0	$ -	0.00		
Longlac, Ontario to Winnipeg	1	$ 732	0.09	$ 732	$ 67
Winnipeg to Edmonton Southline	1	$ 886	0.09	$ 886	$ 81
Winnipeg to Edmonton Northline	0	$ -	0.00		
Saskatoon to Calgary	0	$ -	0.00		
Edmonton to Calgary	4	$ 967	0.36	$ 242	$ 88
Edson to Mountain Park, Alberta	0	$ -	0.00		
Edmonton to Vancouver	0	$ -	0.00		
Tete Jaune, BC to Prince Rupert, BC	0	$ -	0.00		
Western Canada Total	6	$ 2,585	0.55	$ 431	$ 235

Figure 3-20 Division of frost heave caused incidents in Western Canada from 1992 to 2002 by corridor.

3.4.5.11 Icing by Location

As illustrated in Figure 3-21 icing caused incidents are reasonably well distributed across western Canada with the highest annual cost occurring on the Edmonton to Vancouver corridor.



Location summary by corridor of icing caused events. Frequency, severity & annual costs for Western Canada, 1992 to 2002

Corridor	# of events	Cost of events		Frequency (events/year)	Severity (cost/event)		Annual Cost	
Armstrong, Ontario to Winnipeg	6	$	14,659	0.55	$	2,443	$	1,333
Longlac, Ontario to Winnipeg	8	$	7,060	0.73	$	883	$	642
Winnipeg to Edmonton Southline	6	$	10,966	0.55	$	1,828	$	997
Winnipeg to Edmonton Northline	1	$	450	0.09	$	450	$	41
Saskatoon to Calgary	0	$	-	0.00				
Edmonton to Calgary	1	$	-	0.09	$	-	$	-
Edson to Mountain Park, Alberta	0	$	-	0.00				
Edmonton to Vancouver	3	$	80,959	0.27	$	26,986	$	7,360
Tete Jaune, BC to Prince Rupert, BC	5	$	3,337	0.45	$	667	$	303
Western Canada Total	30	$	117,431	2.73	$	3,914	$	10,676

Figure 3-21 Division of icing caused incidents in Western Canada from 1992 to 2002 by corridor.

3.5 CN's Ground Hazard Incident reporting databases.

As described in Section 3.2 two other sources of ground hazard incident reporting information are svsilsble and contain primarily rock landslide information. These include records from both CN amd CPR in BC from 1937 to 1970 and from the CN Ashcroft Subdivisions from 1995 to 2003. The later reporting system was developed and maintained by the author. Following is an analysis of each of these records.

3.5.1 Rock landslide incidents on CN and CP in BC 1937 to 1971

The Peckover (1972) report was produced in response to the formal inquiry into safety of operation in the mountain territory of Canadian National and Canadian Pacific (RTC,1973) by the Railway Transport Committee resulting from a fatal derailment at Mileage 118.9 on CNR's Ashcroft Subdivision on February 15, 1971. Amongst other things, the Peckover report provides a listing of accidents, injuries and fatalities resulting from landslides between 1937 and 1971 on CN and CPR main railway corridors in BC.

Table **3-7** presents a summary of these records sorted according to the landslide type. A comparison of this record to the Canada wide record from 1992 to 2002 presented in Table 3-3 shows that there were an alarming number of injuries and fatalities in this earlier time frame and that obviously hazard management initiatives instituted since that time have been effective. Table 3-1 provides the annual distribution of accidents, injuries and fatalities during 1937 to 1970 that resulted in a disturbing frequency of 3.79 accidents per year, 5.44 injuries per year and 0.71 fatalities per year.

Peckover (1972) included an assessment of the minimal annual direct costs due to rockfall accidents using loss records from the safety and insurance departments of the time for the period from 1966 to 1970. The direct cost from accidents attributable to rockfalls on the CNR BC Southline that runs from Jasper Alberta to Vancouver B.C.was estimated at $360,000 per annum. Accounting for inflation rates from 1972 to 2001 this number inflates to approximately $3,300,000 in 2001 dollars. Surprisingly this compares very closely to the average annual costs from all ground hazard accidents for all of Canada for the time period from 1992 to 2002 reported in Table 3-3 of approximately $3,440,000.

Table 3-7 Casualties from Landslides in BC by landslide type: CN and CP combined 1937 to 1970 (Peckover 1972)

Type of incident	# of Accidents	Fatalities	Injuries	Casualties per accident
struck rock slide	97	22	144	1.71
struck rocks	2	0	2	1.00
struck boulders & rocks	1	0	0	0.00
struck boulder	1	0	0	0.00
struck large rock	1	0	0	0.00
falling rocks struck track motor car	1	0	1	1.00
struck rock and trees	1	0	0	0.00
struck tunnel lining	1	0	1	1.00
Rock Landslides	105	22	148	1.62
struck mud and rock slide	6	0	16	2.67
struck shale slide	3	0	6	2.00
struck mud and shale slide	1	0	2	2.00
struck mud and gravel slide	1	0	2	2.00
Debris Landslides	11	0	26	2.36
struck mud slide	5	0	8	1.60
struck clay slide	1	0	0	0.00
Earth Landslides	6	0	8	1.33
struck snow avalanche	7	2	3	0.71
Snow Avalanches	7	2	3	0.71
TOTALS	**129**	**24**	**185**	**1.62**

Table 3-8 Casalities from Peckover from Landslides hazards in BC by year: CN &CP combined 1937 to 1970

Year	Number of incidents	Fatality	Injury
1937	2	2	4
1938	2	0	9
1939	2	0	3
1940	0	0	0
1941	1	0	2
1942	1	0	3
1943	2	1	3
1944	4	4	5
1945	0	0	0
1946	4	5	4
1947	1	0	5
1948	2	3	3
1949	1	0	4
1950	3	0	4
1951	6	0	11
1952	8	0	10
1953	3	0	4
1954	11	0	14
1955	3	0	11
1956	3	0	6
1957	2	0	0
1958	4	1	32
1959	5	0	3
1960	2	2	4
1961	5	0	6
1962	5	0	3
1963	6	0	7
1964	4	0	0
1965	6	0	0
1966	6	0	3
1967	6	0	2
1968	9	3	14
1969	7	0	6
1970	1	0	0
1971	2	3	0
TOTALS:	**129**	**24**	**185**
Annual Average:	**3.79**	**0.71**	**5.44**

3.5.2 Rock landslide reporting Ashcroft and Yale Subdivisions 1995 to 2003

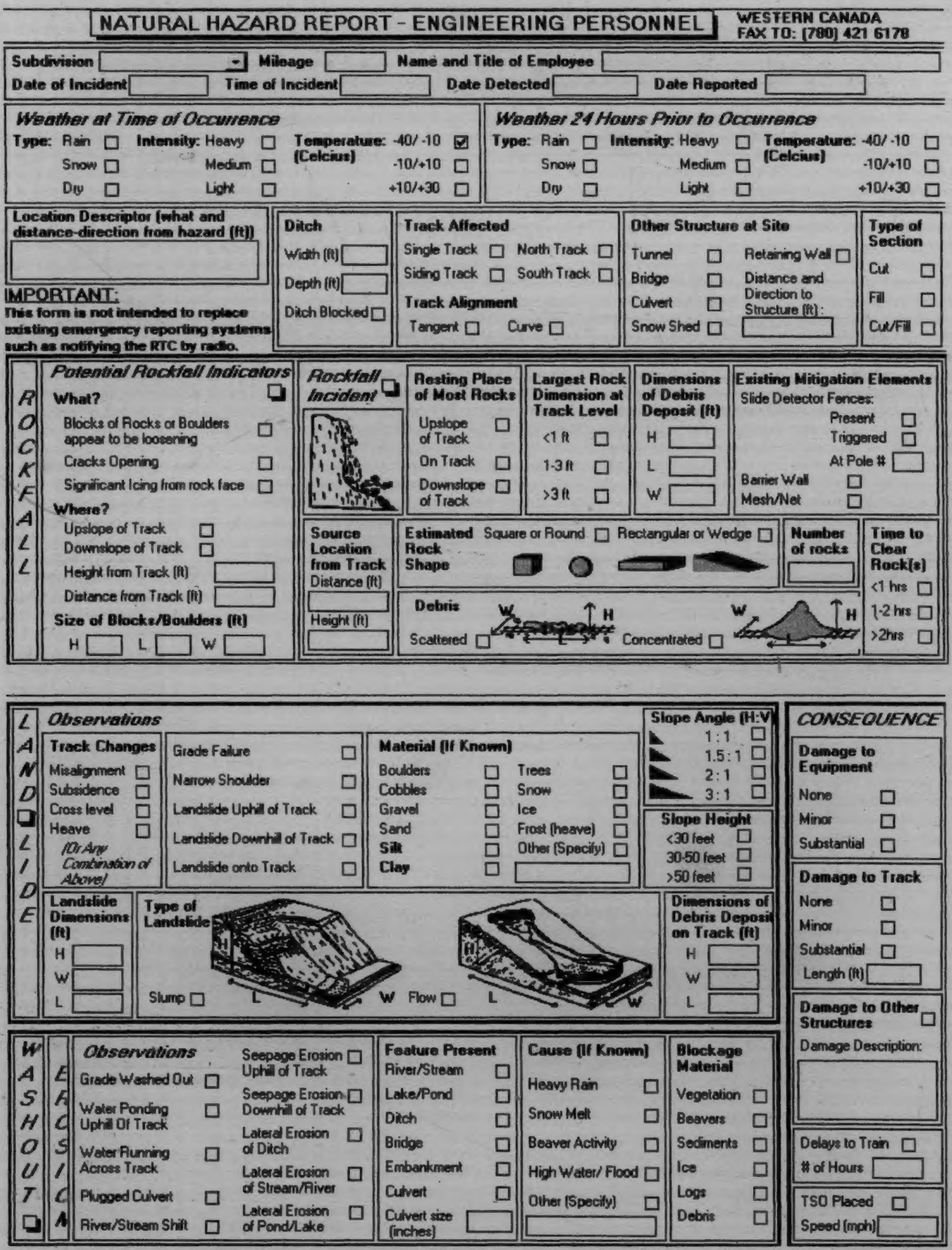
In 1995, in conjunction with the development of the CN Rockfall Hazard and Risk Assessment (CNRHRA) system (Abbott et al, 1998), a field reporting system was initiated on the Yale Subdivision and has continued up to present day. In 1997 it was expanded to facilitate reporting all types of ground hazard events, however this has not been fully utilized to date. Although it was extended in recent years to include other CN subdivisions in British Columbia the most consistent reporting has been of rockfall events from the Yale and Ashcroft Subdivisions. Figure 3-22 illustrates the primary version of the form developed by the author and used to report primarily rockfall incidents from 1995 to 2003. For the purpose of this review, the 1113 rock landslide reports submitted between February 1995 and December 2003 on the Ashcroft and Yale subdivisions were analyzed.

Table 3-9 presents a summary of some of the main statistics from this record. The record indicates that of the average 124 rock landslides reported each year, 71 (57%) came to rest on the tracks. In terms of damage to equipment, which in most cases means trains, there was an average of 2.2 minor damages and 1.2 substantial damages resulting from rock landslides. The severity of track outages resulting from rock landslides averaged 2.75 hours per delay totalling 8 hours per year.

The weather section of the form was included in an attempt to establish any correlation to climatic triggers. The record indicates that for rain the correlation is not strong, only 14% of the reports on the Yale Subdivision indicating rain either at the time or 24 hours preceding the event. There is a stronger correlation for rain at the time of the occurrence on the Ashcroft Subdivision, 38%.

There is a slightly better correlation to rock landslide occurrences and freeze thaw conditions that are inferred to occur when the temperature is between -10°C and +10°C. Overall, 19% of the events occurred on the Yale Subdivision took place when this condition existed, and the correlation is much higher on the Ashcroft at 38%.

This higher correlation on the Ashcroft to both rainfall, and freeze thaw conditions, may be attributable to the fact that the Ashcroft subdivision is in a different ecozone from the Yale Subdivision. The Ashcroft is in the Montane Cordillera ecozone while the Yale is contained in the Montane Cordillera (NRC, 2005). This means that there is a distinct change in characteristic landforms and climate between the two, with the Ashcroft landscape being much more subdued and the climate much dryer than the Yale. Further analysis of the correlation of occurrences to climatic events is included in Chapter 5 in the section on rock landslide triggers.



NATURAL HAZARD REPORT - ENGINEERING PERSONNEL

WESTERN CANADA
FAX TO: (780) 421 6178

Subdivision ☐ **Mileage** ☐ **Name and Title of Employee** ☐
Date of Incident ☐ **Time of Incident** ☐ **Date Detected** ☐ **Date Reported** ☐

Weather at Time of Occurrence

Type: Rain ☐ Snow ☐ Dry ☐
Intensity: Heavy ☐ Medium ☐ Light ☐
Temperature: (Celcius) -40/-10 ☑ -10/+10 ☐ +10/+30 ☐

Weather 24 Hours Prior to Occurrence

Type: Rain ☐ Snow ☐ Dry ☐
Intensity: Heavy ☐ Medium ☐ Light ☐
Temperature: (Celcius) -40/-10 ☐ -10/+10 ☐ +10/+30 ☐

Location Descriptor (what and distance-direction from hazard (ft)) ☐

IMPORTANT:
This form is not intended to replace existing emergency reporting systems such as notifying the RTC by radio.

Ditch
Width (ft) ☐
Depth (ft) ☐
Ditch Blocked ☐

Track Affected
Single Track ☐ North Track ☐
Siding Track ☐ South Track ☐

Track Alignment
Tangent ☐ Curve ☐

Other Structure at Site
Tunnel ☐ Retaining Wall ☐
Bridge ☐ Distance and Direction to Structure (ft): ☐
Culvert ☐
Snow Shed ☐

Type of Section
Cut ☐
Fill ☐
Cut/Fill ☐

ROCKFALL

Potential Rockfall Indicators ☐

What?
Blocks of Rocks or Boulders appear to be loosening ☐
Cracks Opening ☐
Significant Icing from rock face ☐

Where?
Upslope of Track ☐
Downslope of Track ☐
Height from Track (ft) ☐
Distance from Track (ft) ☐

Size of Blocks/Boulders (ft)
H ☐ L ☐ W ☐

Rockfall Incident ☐

Resting Place of Most Rocks
Upslope of Track ☐
On Track ☐
Downslope of Track ☐

Largest Rock Dimension at Track Level
<1 ft ☐
1-3 ft ☐
>3 ft ☐

Dimensions of Debris Deposit (ft)
H ☐
L ☐
W ☐

Existing Mitigation Elements
Slide Detector Fences:
Present ☐
Triggered ☐
At Pole # ☐
Barrier Wall ☐
Mesh/Net ☐

Source Location from Track
Distance (ft) ☐
Height (ft) ☐

Estimated Rock Shape Square or Round ☐ Rectangular or Wedge ☐

Number of rocks ☐

Time to Clear Rock(s)
<1 hrs ☐
1-2 hrs ☐
>2hrs ☐

Debris
Scattered ☐
Concentrated ☐

LANDSLIDE ☐

Observations

Track Changes
Misalignment ☐
Subsidence ☐
Cross level ☐
Heave ☐
(Or Any Combination of Above)

Grade Failure ☐
Narrow Shoulder ☐
Landslide Uphill of Track ☐
Landslide Downhill of Track ☐
Landslide onto Track ☐

Material (If Known)
Boulders ☐ Trees ☐
Cobbles ☐ Snow ☐
Gravel ☐ Ice ☐
Sand ☐ Frost (heave) ☐
Silt ☐ Other (Specify) ☐
Clay ☐ ☐

Slope Angle (H:V)
1 : 1 ☐
1.5 : 1 ☐
2 : 1 ☐
3 : 1 ☐

Slope Height
<30 feet ☐
30-50 feet ☐
>50 feet ☐

Landslide Dimensions (ft)
H ☐
W ☐
L ☐

Type of Landslide
Slump ☐
Flow ☐

Dimensions of Debris Deposit on Track (ft)
H ☐
W ☐
L ☐

CONSEQUENCE

Damage to Equipment
None ☐
Minor ☐
Substantial ☐

Damage to Track
None ☐
Minor ☐
Substantial ☐
Length (ft) ☐

Damage to Other Structures ☐
Damage Description: ☐

Delays to Train ☐
# of Hours ☐

TSO Placed ☐
Speed (mph) ☐

WASHOUT ☐

EROSION

Observations
Grade Washed Out ☐
Water Ponding Uphill Of Track ☐
Water Running Across Track ☐
Plugged Culvert ☐
River/Stream Shift ☐
Seepage Erosion Uphill of Track ☐
Seepage Erosion Downhill of Track ☐
Lateral Erosion of Ditch ☐
Lateral Erosion of Stream/River ☐
Lateral Erosion of Pond/Lake ☐

Feature Present
River/Stream ☐
Lake/Pond ☐
Ditch ☐
Bridge ☐
Embankment ☐
Culvert ☐
Culvert size (inches) ☐

Cause (If Known)
Heavy Rain ☐
Snow Melt ☐
Beaver Activity ☐
High Water/ Flood ☐
Other (Specify) ☐
☐

Blockage Material
Vegetation ☐
Beavers ☐
Sediments ☐
Ice ☐
Logs ☐
Debris ☐

Figure 3-22 Natural Hazard Report form used for reporting rock landslide incidents on the Yale and Ashcroft Subdivisions between 1995 and 2003

Table 3-9 Summary of Rock Landslide Reports for the Ashcroft and Yale Subdivisions, February 1995 to December 2003

Description of Field		Subdivision		Total	Annual Frequency
		Ashcroft	Yale		
1995 to 2003 inclusive	# of rockfall reports	124	989	1113	123.7
Resting Place of Rocks	# on track	64	571	635	70.6
	# upslope	28	428	456	50.7
	# downslope	8	77	85	9.4
Damage to Equipment	Minor	8	12	20	2.2
	Substantial	0	11	11	1.2
Damage to Track	Minor	5	15	20	2.2
	Substantial	0	11	11	1.2
Train Delays	# of Delays	10	16	26	2.9
	Total # of Hours	24.8	47.6	72.4	8.0
	Average delay (hr/delay)	2.48	2.98	2.78	
Weather @ Occurrence	Rain *% of Total Events*	42 *34%*	111 *11%*	153 *14%*	17.0
	Rain Heavy	14	24	38	4.2
	Rain Medium	10	38	48	5.3
	Rain Light	18	49	67	7.4
	-40 to -10 °C	0	0	0	0.0
	-10 to +10 °C *% of Total Events*	47 *38%*	168 *17%*	215 *19%*	23.9
	+10 to +40 °C	14	29	43	4.8
Weather 24 hrs Prior	Rain *% of Total Events*	28 *23%*	126 *13%*	154 *14%*	17.1
	Rain Heavy	10	37	47	5.2
	Rain Medium	9	37	46	5.1
	Rain Light	9	52	61	6.8
	-40 to -10 °C	0	0	0	0.0
	-10 to +10 °C *% of Total Events*	29 *23%*	161 *16%*	190 *17%*	21.1
	+10 to +40 °C	7	30	37	4.1

3.6 Summary

One of the main objectives of Preliminary Analysis is a preliminary assignment of frequency and consequence to the risk scenarios using the structured list of hazards identified. This is accomplished in Chapter 3 through an analysis of the available CN railway ground hazard loss history. The following discussion highlights the main findings from Chapter 3.

A comparison of railway ground hazard events to other railway hazard events in terms of train accident losses for the 1992 to 2002 time period shows that ground hazards occur at a frequency of 8 per year ranking them 4th behind other engineering related causes. In terms of severity, ground hazard causes (excluding the frequent low severity icing derailments) are the highest cost averaging close to $400,000 per accident. Furthermore, these events generated the longest duration of outage per accident. In terms of annual costs, the product of frequency and severity, railway ground hazards ranked third behind track defects and mechanical causes.

These results are not surprising when considering that railway ground hazard incidents usually occur in isolated, high relief locations, often adjacent to a body of water (river or lake). This setting contributes to incrementally higher severity, on average, in terms of injury or fatality, property loss, track outages, recovery time and costs, environmental impacts and liability exposures.

Results of the analysis of the loss record in terms of railway ground hazard types are summarized in . The highest frequency ground hazard causes in the time frame were earth landslides (3.2 per year), followed by rock landslides (2.4 per year). The highest severity ground hazard causes were through flow hazards ($900,000 per accident, on average) followed by earth landslides ($698,000 per accident). The highest annual costs by a large margin were earth landslides ($2,200,000 per year, on average) followed by overland flow erosion ($452,000 per year, on average).

It is apparent that a significant proportion, 63%, of the annual costs from ground hazard events involves complex ground hazards. The most significant events are those that ultimately resulted in an earth landslide. The most significant complex ground hazard event was the earth slide-earth flow event that occurred at Conrad siding at Mile 106.14, Ashcroft Subdivision in March of 1997. This discovery underscores a need to map out the hazard scenarios from the initiating hazard event to the track failure, accounting for all reasonable possibilities.

A review of the variations in annual frequency, severity and costs of train accident losses due to ground hazards, shows that there is a considerable variation of activity from year to year.

The loss analysis by railway ground hazard location indicates that the Edmonton to Vancouver corridor was the most affected by ground hazards in Western Canada in the

1992 to 2002 timeframe. This result is not surprising given the high density of train traffic, the high relief, the density and diversity of natural hazards and the relative youth of the terrain and river systems.

As expected the majority of rock landslide incidents coincide with the mountainous high tonnage corridor between Edmonton and Vancouver.

Debris landslide events primarily affect the Edmonton to Vancouver and Tete Jaune to Prince Rupert corridors, which is not surprising, as these corridors pass through mountainous terrain. These events were primarily the result of channelized debris flows.

Losses resulting from earth landslide events in the 1992 to 2002 time frame again show that the Edmonton to Vancouver corridor was the most difficult corridor by a significant margin. Based on the author's experience this is primarily due to the high relief, the close proximity of the track to major rivers, the youth of this terrain and river system, and the abundance of silty soils along this corridor. Similarly, events on the Tete Jaune to Prince Rupert corridor seem related to their proximity to the river, moderate to high relief, and abundance of both weak clay and silty soils. In the Prairie corridors, earth slides are usually associated with post glacial river valleys, particularly where the tracks descend or ascend the valley slopes. Earth slides that occur on corridors that traverse on to the Canadian Shield primarily in Northern Ontario are observed by the author to occur most commonly at transitions from weak soils to bedrock due to sloping bedrock surfaces, concentrated seepage paths and weak clay and organic soils.

Settlement caused incidents occur more prevalently in the Interior Plains presumably due to the abundance of weak clay subgrades and the lack of drainage in the low relief area.

Overland flow erosion hazard causes are dominated by hazardous beaver activity and thus occur in areas of intense beaver activity in proximity to the tracks such as in Northern Ontario.

There are only four through flow hazard incidents in the database with the most severe incident occurring in Northern Ontario in a calcareous silt subgrade. The propensity of these soils to form cavities is a significant preparatory causal factor for these types of hazards.

There were no incidents related directly to channelized flow erosion. However 10 incidents, most of which were along BC rivers, had river erosion as the penultimate hazard event.

A review of loss records resulting from landslides on both CN and CP between 1937 and 1971 indicate that there were an alarming number of injuries and fatalities resulting from landslides when compared to almost none in recent times. The estimated direct costs resulting from landslide related accidents on CN tracks in BC from 1966 to 1970 was approximately $3,300,000 per annum in 2001 dollars, which is comparable to the recent direct costs resulting from all ground hazards across all of Canada.

A review of a rock fall reporting system implemented on the CN Yale and Ashcroft Subdivisions between 1995 and 2003 indicates that, of the average 124 rock landslides reported each year, 57% came to rest on the tracks, resulting in an average of 2.2 minor damage accidents and 1.2 major damage accidents each year. The average track outage time per delay was 2.75 hours, totaling to 8 hours per year. The record also indicated a 14% correlation of rock falls to rainfall and 19% correlation to freeze thaw conditions. There was a noticeable higher correlation of these two trigger causes on the Ashcroft Subdivision of 38% and 38% respectively. This type of consistent and quantitative incident reporting is essential in the development of the risk management system

Results of the analysis of the loss record in terms of railway ground hazard types is summarized in .

Ground Hazard Causes		Train Accidents: CN Canada Wide (1992-2002) from C.A.R.E.S.						Mitigations: CN Western Canada (1984-2003)			Location of Highest Loss (based on annual direct costs)	Complex Ground Hazards	
Level II Categories	Level III Categories	Events	Injuries	Fatalities	Frequency (events/year)	Severity (cost/event) x1000	Annual Cost x1000	Frequency (mitigations/year)	Severity (costs/mitigation) x1000	Annual cost x1000	Corridor	Preceding Ground Hazard Event	Percentage of Annual Costs
Landslides	Rock landslide	26	1	0	2.4	$ 63	$ 149	10.29	$ 133	$ 1,373	Edmonton to Vancouver	Rock landslide	15%
	Debris landslide	13	2	0	1.2	$ 169	$ 199	0.42	$ 122	$ 51	Edmonton to Vancouver	Rock landslide	1%
	Earth landslide	36	4	4	3.2	$ 688	$ 2,221	3.76	$ 227	$ 862	Edmonton to Vancouver	Debris landslide Earth landslide Subsidence Overland flow Through flow Subaqueous flow *Total*	3% 52% 10% 8.0% 0.1% 5.0% 78.0%
Subsidence	Settlement	15	0	0	1.4	$ 28	$ 39	0.17	$ 68	$ 11	Saskatoon to Calgary	none	0.0%
	Collapse	1	0	0	0.1	$ 2	$ 0	0.00	$ -	$ -	no events	none	0.0%
Hydraulic erosion	Overland flow	12	0	0	1.1	$ 414	$ 452	0.17	$ 291	$ 49	Longlac to Winnipeg	Debris flow Sub aqueous flow	1.0% 1.0%
	Through flow	4	3	0	0.4	$ 901	$ 328	0.13	$ 170	$ 21	Longlac to Winnipeg	Collapse	97.0%
	Sub aqueous flow	0	0	0	0.0		$ -	0.42	$ 226	$ 94	no events	none	0.0%
Ice & snow	Snow avalanche	1	0	0	0.1	$ 79	$ 7	16.00	$ 10	$ 160	Edmonton to Vancouver	none	0.0%
	Frost heave	12	0	0	1.1	$ 4	$ 4	0.34	$ 60	$ 3	Edmonton to Calgary	none	0.0%
	Icing	305	0	0	27.7	$ 2	$ 43		$ -	$ -	Winnipeg to Edmonton (South line)	none	0.0%
	Total	**424**	**10**	**4**	**38.55**	**$ 89**	**$ 3,441**	**16.4**	**$ 160**	**$ 2,454**			**60.0%**

Table 3-10 Summary of ground hazard event and mitigation loss analysis for CN Western Canada

Chapter 4 Railway Ground Hazard Risk Characterization Methodology

4.1 Introduction

In this chapter, the author proposes a methodology to systematically characterize railway ground hazards for use in risk assessment and ultimately in risk management. The proposed methodology developed is able to systematically record railway ground hazard observations and experience, and is a tool for predicting future railway ground hazard events and characterizing the risk associated with them. Information collected in this manner is structured for use in both qualitative and quantitative risk assessments. As well, it allows for the consistent comparison of risk between railway ground hazards and the eventual comparison with other railway hazard risks.

To adequately characterize the risk of railway ground hazards, it is necessary to investigate the mechanistic, spatial and temporal characteristics of the entire risk scenario that can lead to a track failure and loss to the railway and then present and apply the results as a standardized characterization system. This structured understanding of the events that result in loss to the railway provides an effective tool for identification, prediction, control and monitoring of railway ground hazards.

Consistent with the railway ground hazard classification system, the characterization system is designed to be open. As new aspects become apparent, they can easily be added to the glossary of terms, without compromising the structure and functionality of the characterization system.

This chapter covers a description of the railway ground hazard risk scenario and its relevance to the risk algorithm (probability x severity). It then describes the methods to characterize each of the factors that make up the algorithm, namely, the railway ground hazard scenario probability, track vulnerability, service disruption vulnerability, derailment vulnerability and finally the consequence severities.

The following chapter, Chapter 5, presents the results from a rudimentary field application of this methodology on railway ground hazards on CN in Western Canada. Chapters 6 through 11 use this methodology to characterize the predominant railway ground hazard risk scenarios. In each of these chapters, a preliminary glossary of ground hazard preparatory and trigger causal factors for each of the railway ground hazard classes is provided, to be used with the risk characterization methodology developed in this chapter.

4.2 The Railway Ground Hazard Risk Scenario

To appropriately characterize railway ground hazards for risk assessment purposes, it is required to identify and characterize the entire risk scenario. CSA Q850-97 (CSA, 1997) defines a risk scenario as a defined sequence of events with associated frequency and consequences. In this Thesis a railway ground hazard risk scenario is comprised of a railway ground hazard scenario, track failure and consequences or loss to the railway.

The railway ground hazard scenario maps the risk scenario from the initial hazard event through to track failure. A track failure occurs when the track ceases to be safe for train traffic at the posted track speed. Ground hazard events may result in a track failure by:

- Removing support from the track structure;
- Blocking the track;
- Striking a train;
- Deflecting the track rail surface;
- Changing the track gauge;
- Damaging the track components; or
- Damaging track structures such as bridges or retaining walls.

Consequences to the railway are defined in terms of severity of track failure, service disruption or derailment.

Consistent with Wong (1998) the risk associated with the railway ground hazard risk scenario can be expressed as Equation (4-1).

Risk = Ground Hazard Scenario Likelihood **x** Consequence Likelihood **x** Severity(4-1)

The *ground hazard scenario likelihood* is the probability that a ground hazard scenario will occur at a given location and will affect the track. For instance, this would comprise an estimate of the likelihood that rocks will detach, transport and reach the track.

The *consequence likelihood*, given the ground hazard scenario occurs is the probability that consequences such as track failure, service disruption or derailment will occur. For instance, given a rockfall event has resulted in rock on the track, the likelihood reflects whether this would result in unsafe track, a service disruption or a derailment.

Severity is the predicted magnitude of direct and indirect loss resulting from track failure, derailment or service disruption.

The overall characterization approach proposed here for railway ground hazards involves qualifying and, if necessary, quantifying engineering judgement in accordance with Equation (4-1) by:

1. Identifying, describing and determining the state of the railway ground hazard risk scenario up to the point of track failure;
2. Developing a set of causal factors that indicate that the ground hazard exists and associated attributes that provide an indication of likelihood of the hazard occurrence and the probability of a railway ground hazard scenario failure;
3. Identifying the factors relating to track vulnerability, service disruption vulnerability, and derailment vulnerability that when combined, provide an estimate of likelihood of track failure, service disruption or derailment, resulting from the railway ground hazard scenario.
4. Identifying factors relating to the severity of losses resulting from track failure, service disruption or derailment. These factors tend to be location specific; they include access, working room, proximity to a water body, height and angle of the downhill slope or volume and type of rail traffic.

The product of the probability of hazard scenario occurrence and consequence likelihood gives the estimated probability of track failure, service disruption or derailment. The product of the probability of track failure, service disruption and derailment and the corresponding severity gives an estimate of the corresponding risk of each of these consequences. If the units of severity were the same, such as dollars, a summation of these individual risks would yield the total risk associated with the railway ground hazard risk scenario. It follows from this that the system to be used to identify and characterize the risk associated with railway ground hazards would have the same structure as Equation (4-1).

As an example, the CN Rockfall Hazard and Risk Assessment (CNRHRA) system (Pritchard, 2005) uses this algorithm to assess the derailment risk to the railway associated with rockfalls. Because the CNRHRA system is one of the established quantitative risk assessment models for rockfall hazards at CN, applying a similar approach to other ground hazards allows eventual risk comparisons between hazards. Following is a short description of the basic algorithms used in the CNRHRA.

The CNRHRA defines the various parameters in Equation (4-1) as described in Table 4-1.

Table 4-1 Summary of the CNRHRA rock fall hazard risk scenario equation factors.

Railway Ground Hazard Risk Equation Factor	**Corresponding CNRHRA Rockfall Hazard Risk Equation Factors**
Ground Hazard Scenario Likelihood	1. Hazard scenario = Rockfall 2. Hazard Likelihood = Rockfall Frequency (RF)
Derailment consequence likelihood	3. Vulnerability = (Vspat * Vtemp * Vloss) = Derailment Hazard (DH) where: • Vspat = probability of spatial impact (the likelihood of debris reaching the track); • Vtemp = probability of temporal impact (the likelihood that a train strikes debris and expressed as Avoidance Factor (AF)); and, • Vloss = probability of loss (derailment given impact with slide debris).
Severity	4. Consequence = Consequence Factor (CF) = severity of loss from derailment

The risk algorithm, with application of the CNRHRA terms, becomes Equation (4-2)

Derailment Risk Rating (DRR) = Rockfall Frequency (RF) Score x Derailment Hazard (DH) Score x Consequence Factor (CF) (4-2)

4.3 Outline of the Railway Ground Hazard Risk Characterization System

The four components of the proposed railway ground hazard risk characterization system are:

1. Characterize the railway ground hazard scenario:
    - Sequence of hazard events leading to track failure
    - Ground conditions
    - Processes
    - Rates and timing of railway ground hazard scenario failure
    - Ground hazard event stage and track stability state of railway ground hazard scenarios
2. Identify ground hazard preparatory and trigger causal factors and attributes in the following categories:
    - Ground conditions
    - Geomorphological processes
    - Physical processes
    - Man or animal made processes
3. Identify consequence likelihood factors in the following categories:
    - Track vulnerability
    - Service disruption vulnerability
    - Derailment vulnerability
4. Identify severity factors in the following categories:
    - Track failure - direct losses from infrastructure damage
    - Service disruption – indirect losses from lost revenue
    - Derailment – direct and indirect losses from derailment

At the end of this characterization exercise, sufficient information should be collected about the specific railway ground hazard to complete the risk equation (4-1).

Figure **4-1** is a schematic depicting the railway ground hazard risk scenario characterization system. The remainder of this chapter is dedicated to a description of these four steps for use in the subsequent chapters.

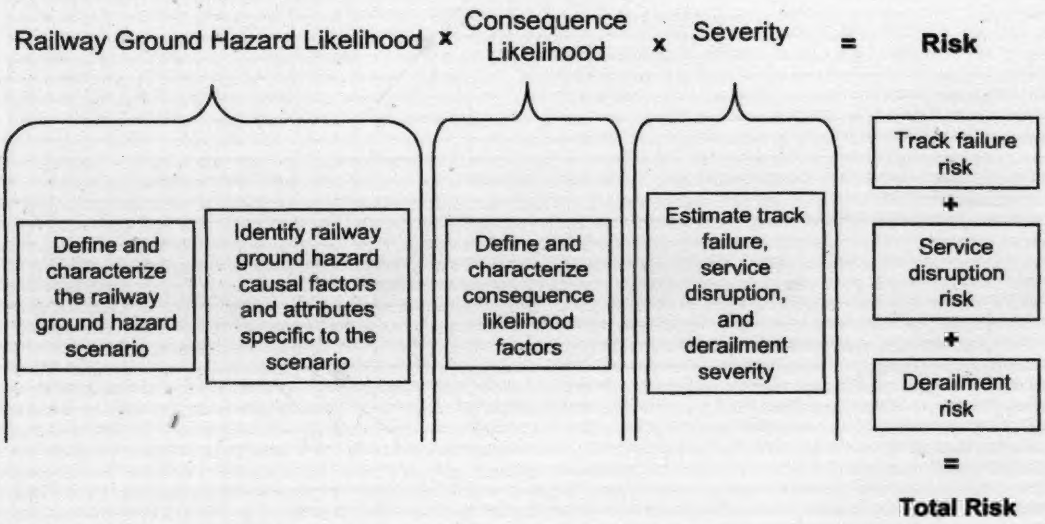

Railway Ground Hazard Likelihood
x
Consequence Likelihood
x
Severity
=
Risk
Define and characterize the railway ground hazard scenario
Identify railway ground hazard causal factors and attributes specific to the scenario
Define and characterize consequence likelihood factors
Estimate track failure, service disruption, and derailment severity
Track failure risk
+
Service disruption risk
+
Derailment risk
=
Total Risk

Figure 4-1 Illustration of the railway ground hazard risk scenario characterization system.

4.4 Characterization of Railway Ground Hazard Scenario

This section develops the methodology for characterizing the railway ground hazard scenario by presenting methods to map out the scenario; describe the ground conditions, processes, rates of movement and timing of the ground hazard events; and assign a stage of activity to each railway ground hazard event and a track stability state for each branch of the event tree. Characterization of the remainder of the risk scenario, assuming the ground hazard scenario affects the track, is addressed under the headings of track vulnerability (4.6.1), service disruption vulnerability (4.6.2), derailment vulnerability (4.6.3) and severity (4.7).

4.4.1 Railway Ground Hazard Scenario: Failure Mode and Effect Analysis (FMEA)

Results from Section 3.4.4 "Losses from Complex Ground Hazards" indicate that 63% of the annual costs from train accidents attributed to ground hazard events involved complex ground hazards. From this result and from the author's experience it was apparent that to properly characterize the ground hazard scenario, the methodology would need to map out all possible combinations of ground hazard events that could result in track failure. Thus railway ground hazard scenarios are described here using failure mode and effect analyses, where the individual railway ground hazard events represent system component failures that can occur in series or parallel, to ultimately result in track failure. The methodology requires that each railway ground hazard location identified be assigned a FMEA that appropriately represents all likely combinations of ground hazard events that can lead to track failure at that location.

In this methodology, the railway ground hazard location is named after the type of railway ground hazard scenario identified for that location. In its simplest form, it is the name given to either the simple or complex railway ground hazard. The individual ground hazard event within the scenario uses the terminology developed in Chapter 2 for classification of railway ground hazard events. A rock fall hazard scenario, for example, describes a single ground hazard event whereby a rock or rocks fall, bounce or roll from their source location and end up on or near the track, creating a likelihood of track failure because the rocks may be of sufficient size, distribution, quantity and location to make it unsafe for trains to pass this location at track speed. A bank erosion-earth slide hazard, on the other hand, describes a complex railway ground hazard whereby multiple ground hazards may act in series to create a likelihood of track failure.

More complicated ground hazard scenarios can occur both in series, resulting in AND statements, and in parallel, resulting in OR statements, to create more than one likelihood of track failure. This prompts the use of a failure mode and effect analysis method (FMEA) to appropriately map out the fault tree that can lead to track failure. A FMEA selects a failure within a system component (a railway ground hazard event) and then, using a logic tree, projects the effects of this one failure on other system components and on the overall system (Head, 1995). Figure 4-2 is a simplified FMEA depicting a relatively complex but surprisingly frequent railway ground hazard scenario that initiates with a debris flow and can fail the track via a number of series and parallel pathways. This particular railway ground hazard scenario is described in Chapter 7.

The suggested nomenclature for a complex ground hazard scenario of this type uses an en dash (-) (Cruden and Varnes, 1996) to denote a series linkage and introduces a forward slash (/) to denote a parallel connection. This railway ground hazard scenario would then be termed:

Debris flow – Avulsion – Debris flow / Gullying / Seepage erosion / Earth slide – Earth flow.

Using the glossaries for railway ground hazards in Chapter 2, the abbreviated name for this hazard scenario becomes DFw – Av – DFw/GE/SE/ESI – EFw. It is recognized that this nomenclature fails to specify all linkages to track failure or indicate the types of track failure possible from each branch. The reader is referenced to the FMEA diagrams for this information.

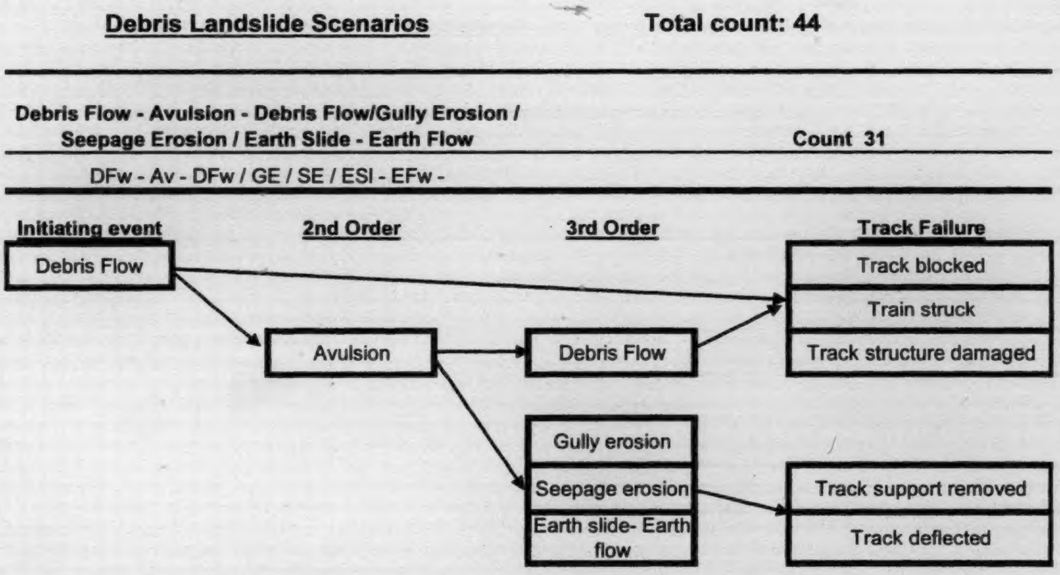

Debris Landslide Scenarios
Total count: 44
Debris Flow - Avulsion - Debris Flow/Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow
Count 31
DFw - Av - DFw / GE / SE / ESI - EFw -
Initiating event
2nd Order
3rd Order
Track Failure
Debris Flow
Avulsion
Debris Flow
Gully erosion
Seepage erosion
Earth slide- Earth flow
Track blocked
Train struck
Track structure damaged
Track support removed
Track deflected

Figure 4-2 Simplified FMEA depiction of a typical complex railway ground hazard scenario that starts with a debris flow event.

4.4.2 Ground Conditions

Essential to understanding the behaviour and processes involved in a ground hazard event is knowledge of the primary ground conditions involved. It is essential not only in understanding the processes and engineering properties and behaviours but also as a means of associating the ground conditions to a particular ground hazard in the identification of ground hazards. Development of a representative geologic model can add significant understanding of ground conditions relevant to certain ground hazards.

In the case of landslides, the predominant material type involved in the movement is included as part of the landslide name as rock, debris or earth. Cruden and Varnes (1996) state that …"This division of soils is crude, but it allows the material to be named by a swift and even remote visual inspection." In order to start correlating the material type to its specific engineering properties and behaviour, further definition of the landslide material types is necessary.

Although the classification of the other Level II classes of railway ground hazards, namely subsidence, hydraulic erosion, snow avalanches and icing, is process based, it is no less important to identify the primary materials involved in these processes. Hydraulic erosion, for instance, is highly dependent on the particle size distribution and for non-cohesive sediments, the spatial distribution of sediment sizes, both horizontally and vertically. For cohesive soils, the erodibility is complex due to the complex physio-chemical interactions between colloidal particles, the effects of pore pressures and the effects of preloading. As part of the detailed characterization of these ground hazards in Chapters 6 through 11, the predominant soil types and properties associated with each ground hazard type is discussed.

For debris and earth soils, gravel sizes and down, the unified soil classification system is adopted (Wagner, 1957). The three main classes in this system are:

- Coarse grained (more than 50% larger than 63 mm BS sieve size)
- Fine grained (more than 50% smaller than 63 mm BS sieve size)
- Highly organic soils

Size distribution, material types (rock, trees etc.), shape and angularity, are generally used to describe debris soils, which are by definition predominantly larger than sand sizes.

Rock material is characterized according to its relevant geological conditions at site, such as rock types, stratigraphy, discontinuities, seepage and weathering. As well there are methods developed to classify the rock mass at the site which include:

1. The CSIR rating (Bieniawski, 1974), a geomechanics classification of rock mass that generates a rock mass rating (RMR) used initially in tunnel applications.
2. The NGI (Barton, 1974) classification system developed to estimate the shear strength properties of a rock mass.

These methods are generally used in more detailed applications to estimate the shear strength parameters for a rock slope stability analysis.

Although the definition of a snow avalanche taken from the Land Managers Guide to Snow Avalanche Hazards in Canada (CAA, 2002(b)) stated that snow avalanches may contain rock, broken trees, soil, ice or other material, the predominant controlling material is snow. According to the CAA (2002(b)), the main types of snow that control snow avalanche behaviour include:

- Cohesive snow
- Low-cohesive snow
- Dry snow (no liquid water between particles)
- Wet snow (contain liquid water between particles)
- Slush (consists of snow soaked with water)

Similarly for icing hazards, the predominant controlling material is ice. There are a variety of types of ice including:

- Ice lenses: associated with frost heaves
- Aufeis: the accumulation of ice that forms when liquid water spreads out in sheets and freezes (AGI, 1976).
- River Ice (Ashton,1986):
    - Border ice
    - Frazil ice
    - Anchor ice

4.4.3 Processes

The processes section of the railway ground hazard scenario characterization addresses the kinematics of failure of the individual ground hazard event. For landslides, it characterizes the type of movement of a mass of rock, debris or earth down a slope.

Cruden and Varnes' (1996) methodology for describing landslide types and processes is used in this Thesis to describe potential landslide processes. This methodology was used as the basis for the railway ground hazard classification system introduced in Chapter 2 and has additional descriptors and conventions useful for characterizing the landslide features, geometry, dimensions, distribution and style of the movement, water content, and a full description of the types of movement.

A railway subsidence hazard is defined as a downward displacement of the track associated with compression or displacement of materials in the track road bed specifically the ballast, sub grade, embankment or underlying foundation. In this case it is the kinematics of failure of the track roadbed system that needs to be described. Level III categorization of subsidence is based on the long-term rate of movement. Settlement is a slow or incremental process resulting from compression, consolidation, incremental plastic deformation or incremental dynamic liquefaction. The latter two processes result from dynamic train loading. These settlement processes are used for the level IV categorization as described in Table 2-5. Conversely, collapse is a sudden occurrence usually associated with vertical displacement into a void. As such, level IV categorization of collapse hazards is based on the process that has either caused the void to form or caused the ground to suddenly lose all its strength as in the case of liquefaction. Types of railway collapse hazards are listed and described in Table 2-6.

Hydraulic erosion involves removal of soil particles or rock by the action of flowing waters. For hydraulic erosion, it is the kinematics of this action failing either the track road bed system or the slope system that need to be described. A description of the modes of movement or processes for hydraulic erosion is contained in the railway hydraulic erosion hazard classification system. Level III categorization of railway hydraulic erosion hazards is based on the slope hydrologic cycle into overland flow, through flow and sub-aqueous flow. Level IV categorization is based on process type as described in the railway hydraulic erosion hazard classification system presented in Table 2-7 with a sub reference to

Table **2-8** for level V categorization of channelized flow erosion hazards.

4.4.4 Rates, Timing and Lag Time within a Railway Ground Hazard Scenario

To characterize the rates of system failure that can ultimately result in track failure within a railway ground hazard scenario it is required to estimate the typical rate and timing of the individual ground hazard events, which can be considered as components in the system, and the lag time that may exist between the hazard events.

The rate characterization can be a measure of either the continuous or cumulative incremental non-recoverable movements involved in the ground hazard event. A fall or flow, for instance, is usually continuous at a typical rate of movement, whereas a slide, erosion, or track settlement tends to be intermittent dependent on the intermittent nature of the process causal factors. Examples of intermittent causal factors may include discrete train loading, freeze-thaw processes or intense rain events. When the intermittent movements are small but non-recoverable, the rates are estimated as the cumulative movements over time.

The rate of the slope system failure by landslides is characterized using the velocity scale proposed by Cruden and Varnes (1996).

The rate of sub-grade system failure by subsidence is contained in the Level III classification of subsidence hazards. Settlement is a slow or incremental process resulting from compression, consolidation, plastic deformation or incremental dynamic liquefaction. Collapse is a rapid movement usually associated with vertical displacement into a void that was formed some time before the event.

The rate of the slope or sub-grade system failure by hydraulic erosion is also characterized using the velocity scale proposed by Cruden and Varnes (1996)

For landslides and snow avalanches, rates of movement, coupled with size, determine the mobility and magnitude of the event that provides an indication of the destructive ability of the event. The CAA (2002(b)) does not have specific criteria for classifying the rate of snow avalanche movement but rather has developed a classification system for avalanche size that includes an estimate of the impact pressure from an avalanche. The impact pressure is defined as the avalanche force per unit area perpendicular to a planar surface such as a wall. The pressure is proportional to flow density and the square of flow velocity.

The timing of the ground hazard event corresponds to the timing of the primary trigger causal factors, defined in Section 4.5.1.2, identified and assessed for the individual ground hazard event. For example:

- As presented in Section 3.5.2, the frequency of rock falls in the Fraser Canyon, BC spikes in January and February of the year, corresponding with the maximum number of daily freeze-thaw cycle trigger causal factors in any given year.
- Local scour or bank erosion hazard events in the lower Fraser River in BC are triggered by high flows in the river which invariably occur in late May- early June of each year.
- In a specific case observed by the author, daily rock fall hazard events only occurred after 12 noon, triggered by the sun hitting the rock slope at that time of the day, melting the remnant snow.

As railway ground hazard scenarios may consist of more than one ground hazard event that must act in series to affect track failure, any lag time between the serial ground hazard events becomes an essential parameter required to estimate the rates of system failure within the railway ground hazard scenario.

The rate and timing of ground hazard events and the lag time between the events within the overall scenario has a direct bearing on the ability of the railway to react to the event to mitigate, protect or warn against track failure, service disruption or derailment. As well, understanding the rates and timing of hazard events and lag time between them, in the context of the mapped out railway ground hazard scenario, allows for the effective planning of monitoring and mitigation.

4.4.5 Track Stability State of ground hazard scenario

A key aspect in the characterization of the railway ground hazard risk scenario is to establish the status of a ground hazard within the identified ground hazard scenario and its relative effect on track failure. This provides the decision-maker with an invaluable indicator of how close the site may be to track failure and a prediction of what is likely to happen next. It also allows a correlation to the relevant controlling laws and parameters; preparatory and triggering causal factors; and the type of track failure.

4.4.5.1 Literature Review

A review of the literature provided three suggested methodologies to categorize either the state of stability or the stage of movement of a landslide system (Popescu, 1994, Cruden and Varnes, 1996, and Lerouiel et al, 1996). Each of these methodologies is reviewed and a combined criterion is suggested to correlate the state of stability of the track from the landslide activity to the stage of the landslide movement. The presence or absence of causal factors is introduced as a means of discerning the state of track stability. A parallel criterion is then developed and presented to assess the state of track stability for all Level II railway ground hazard scenarios namely landslides, subsidence, hydraulic erosion, snow avalanches and icing.

Popescu (1994) presented a proposal by the Working Party on World Landslide Inventory of an operational approach for classification of landslide causal factors for use in reporting landslides, as proposed by the WP/WLI(1990, 1991). The approach developed by Crozier (1986) visualizes the slopes in one of three stability stages as follows:

1. Stable: slopes where the margin of stability is sufficiently high to withstand all destabilizing forces.
2. Marginally Stable: Slopes which will fail at some time, in response to destabilizing forces attaining certain level of activity.
3. Actively Unstable: Slopes for which destabilizing forces have produced continuous or intermittent movement.

Using the three stability stages as a useful framework for understanding the causal factors for landslides, the Working Party (Popescu, 1994) proposed classifying the causal factors into two groups based on their function:

1. Preparatory causal factors: make the slope susceptible to movement without actually initiating it, thereby tending to place the slope in a marginally stable state.
2. Triggering causal factors: initiate movement, thereby shifting the slope from marginally stable to an actively unstable state.

A particular causal factor can perform either or both functions, depending on its activity and the margin of stability. The proposed classification system divides the causal factors according to their effect, either preparatory or triggering, and their origin, either ground conditions or geomorphological, physical or man-made processes. Ground conditions may not have a triggering function, while any ground condition or process may have a preparatory function.

The operational approach proposed by Popescu (1994) is appropriate for landslide hazards only and addresses only a "slope system failure".

Cruden and Varnes (1996) propose a similar stage of slope system failure classification referred to as the state of activity, in which they describe four primary states of landslide activity as follows:

- **Active**: Landslide that is currently moving, including both first-time movements and reactivations.
- **Reactivated**: Landslide that is again active, after being inactive.
- **Suspended**: Landslides that have moved in the last annual cycle of seasons, but are not moving at present.
- **Inactive**: Landslides that last moved more than one annual cycle of seasons ago subdivided as follows:
    - **Dormant**: Where the causes of the movement remain apparent
    - **Abandoned**: Where the causes of the movement are no longer apparent
    - **Stabilized**: Where artificial remedial measures have stopped the movement
    - **Relict**: Where there is only remnant evidence of a previous movement and the causes of the movement are no longer apparent

Compared to Popescu (1994), the Cruden and Varnes (1996) classification subdivides the actively unstable (active) state into active or reactivated movement and the stable (inactive) state into dormant, abandoned, stabilized and relict. It does not however make a clear distinction between stable and marginally stable slopes and does not account for the causal factors in the designation of the state of activity. It might be argued that the suspended or inactive dormant states are in the marginally stable stage, as their definitions imply that preparatory causal factors exist currently.

The third suggested method for mapping the activity state of landslides is from Lerouiel et al (1996), in which they describe a three dimensional characterization matrix. The matrix axes are type of material, type of movement and stage of the movement. The four stages of slope movement suggested by Vaunat et al (1994) and Leroueil et al (1996) are listed below:

1. The pre-failure stage, including all the deformation processes leading to failure. This stage is controlled mostly by deformations due to changes in stresses, creep and progressive failure.
2. The onset of failure, characterized by the formation of a continuous shear surface through the entire soil mass.
3. The post-failure stage, which includes movement of the soil mass involved in the landslide, from after failure until it essentially stops. It is generally characterized by an increase of the displacement rate followed by a progressive decrease in velocity.
4. The reactivation stage, when soil mass slides along one or several pre-existing shear surfaces.

Introduction of the 3rd axis, stage of movement, allows classification of the slope movement according to its current status in relation to the overall landslide hazard scenario.

The approach proposed by Leroueil et al. (1996) compares reasonably well to both Popescu (1994), and Cruden and Varnes (1996) in terms of the distinction between the various stages of landslide movement, and introduces the identification and use of the controlling laws and parameters which can be different, depending on the current stage of movement. However, the use of the term pre-failure is felt to be somewhat limited, as it gives the connotation that failure is inevitable. As well, the use of failure in this context is limited to the failure of the slope system that may or may not imply failure of the track.

There are a number of circumstances where the railway is laid on failed slopes, but the track has not failed. There are also numerous circumstances where a ground hazard event occurs, but only serves to prepare or trigger a subsequent ground hazard event to potentially result in track failure. The more appropriate terminology to describe the status of a railway ground hazard within its hazard scenario is that suggested by Crozier (1986) which places the landslide, in this case, into stable, marginally stable or actively unstable states. The equivalence between the two terminologies is suggested in Table 4-2. Cruden and Varnes (1996) terminology is adopted to describe the stage of landslide movement in Table 4-2.

Table 4-2 Suggested correlation between Crozier (1986) and Leroueil et al. (1996) terminology for states of landslide stability

Crozier (1986)	**Leroueil et al. (1996)**
Stable	None applicable
Marginally stable	Occasional reactivation, Prefailure, Post failure
Actively unstable	Onset of failure, Active landslide

4.4.5.2 Track Stability State and Landslide Movement Stage

Based on the preceding review of the three suggested methodologies for classifying the state of stability or the stage of movement of a landslide system, Table 4-3 is proposed by the author as a practical means to subjectively assess track stability states from landslide activity within a landslide hazard scenario using identified causal factors. Table 4-3 introduces a correlation of the track stability state to the stage of landslide movement. This presupposes that the potential or actual landslide movement will directly result in track failure as defined in Section 4.2. If the landslide hazard event in question can not directly affect the track stability, then Table 4-3 only describes the landslide movement stage. This approach is expanded in Section 4.4.5.3 to subjectively assess the ground hazard activity stage and the track stability state for all railway ground hazards.

The characterization of track stability state, designated as an integer 1 to 4 in Table 4-3, plays a practical role in the management of railway ground hazards because the ratings are related to the required action and monitoring of a specific railway ground hazard.

A railway landslide hazard is assessed as a ***4**, stable state*, if the margin of stability of the slope system that can affect the track is sufficiently high to withstand all destabilizing processes. Railway landslide hazards in this state are identified by the presence of ground condition causal factors but the absence of any significant process related causal factors. The landslide movement stages that correspond to this state for the landslide hazard events that immediately precede track failure are:

- Abandoned, where the process causal factors of the movement are no longer apparent;
- Stabilized past one season, where artificial remedial measures have stopped the movement and more than one cycle of seasons has passed; and
- Relict, where there is only remnant evidence of a previous movement and the process causal factors of the movement are no longer apparent.

A railway landslide hazard is subjectively assessed as a ***3**, stable state – monitoring required*, if the margin of stability of the slope system that can affect the track is once again sufficiently high to withstand all destabilizing processes. However in this case there are significant preparatory process causal factors present to warrant periodic monitoring of the site. The landslide movement stages that correspond to this state for the landslide hazard events that immediately precede track failure are:

1. Preparatory, where no movements have occurred but preparatory process causal factors are apparent;
2. Stabilized recently, where artificial remedial measures have stopped the movement but less than one cycle of seasons has passed; and
3. Dormant, where the causes of the movement remain apparent but last moved more than one annual cycle of seasons ago.

A railway landslide hazard is subjectively assessed as a **2**, *marginally stable state*, if the slope system that can affect the track will fail at some time in response to destabilizing processes attaining certain levels. Certain levels for landslide hazards refer to predetermined rates and volumes of movement dependent predominantly on the mode of track failure as defined in Section 4.6.1. This state is subjectively assessed if there are triggering causal factors identified that can make the track actively unstable. The landslide movement stages that correspond to this state for the landslide hazard events that immediately precede track failure are:

- Marginal, where no movements have occurred but preparatory and triggering causal factors are apparent; and

- Suspended, landslides that have moved in the last annual cycle of seasons but are not moving at present.

A railway landslide hazard is subjectively assessed as an ***1**, actively unstable state*, if destabilizing processes affecting the slope system that can affect the track have produced continuous or intermittent track failure by attaining certain levels. Certain levels for landslide hazards refer to predetermined rates and volumes of movement dependent predominantly on the mode of track failure as defined in Section 4.6.1. The landslide movement stages that correspond to this state for the landslide hazard events that immediately precede track failure are:

- Active, landslide is currently moving; and
- Reactivated, landslide is again active after being inactive.

Table 4-3 Suggested track stability states and movement stages for railway landslide hazard scenarios

Track Stability State		**Landslide Movement Stage**	
(4) Stable	Margin of stability is sufficiently high to withstand all destabilizing processes Only ground condition causal factors apparent	**Abandoned**	Where the process causal factors of the movement are no longer apparent
		Stabilized past one season	Where artificial remedial measures have stopped the movement and more than one cycle of seasons has passed.
		Relict	Where there is only remnant evidence of a previous movement and the process causes of the movement are no longer apparent
(3) Stable-monitoring required	Margin of stability is sufficiently high to withstand all destabilizing processes Preparatory process causal factors apparent but triggering causal factors can not make the track actively unstable	**Preparatory**	Where no movements have occurred but preparatory process causal factors are apparent
		Stabilized recently	Where artificial remedial measures have stopped the movement but less than one cycle of seasons has passed
		Dormant	Where the causes of the movement remain apparent but last moved more than one annual cycle of seasons ago
(2) Marginally Stable	Slopes that will fail at some time in response to destabilizing processes attaining certain levels. Triggering causal factors can make the track actively unstable	**Marginal**	Where no movements have occurred but preparatory *and* triggering causal factors are apparent
		Suspended	Landslides that have moved in the last annual cycle of seasons but are not moving at present
(1) Actively Unstable	Destabilizing forces have produced continuous or intermittent track failure	**Active**	Landslide that is currently moving
		Reactivated	Landslide that is again active after being inactive

4.4.5.3 Track Stability State and Ground Hazard Scenario Stage

The next step in this exercise is to extend this criterion into a generic criterion that covers all Level II railway ground hazard scenarios, involving combinations of landslides, subsidence, hydraulic erosion, snow avalanches and icing hazard events.

The first step to achieving this extension is to redefine the states of track stability and causal factors to be generic to all railway ground hazards as follows:

- Stable: track has a margin of stability sufficiently high to withstand all destabilizing processes from the railway ground hazard event that can directly affect the track.
- Marginally Stable: track which will fail at some time in response to the destabilizing processes from the railway ground hazard event attaining a certain level.
- Actively Unstable: track for which destabilizing processes from the railway ground hazard event have produced continuous or intermittent track failure.
- Preparatory causal factor: conditions or processes that make the railway ground hazard more likely without causing the event to occur. If the railway ground hazard in question can directly affect the track, the presence of preparatory causal factors can move the track from stable to marginally stable as it also makes track failure more likely.
- Triggering causal factor: initiates the railway ground hazard event. If the railway ground hazard in question can directly affect the track, the presence of trigger causal factors can move the track from marginally stable to an actively unstable state.

The other change necessary to extend the criterion to cover all railway ground hazards is to replace the term *movement,* for describing the stage of landslide processes, with *activity,* for describing the stage of generic ground hazard processes.

Table 4-4Table 4-4 presents the proposed generic criterion to subjectively assess track stability states from railway ground hazard activity within a railway ground hazard scenario using identified causal factors. Similar to the landslide criterion, Table 4-4, introduces a correlation of the stability state to the stage of the railway ground hazard activity. Again, this presupposes that the potential or actual railway ground hazard event will directly affect the track, introducing a likelihood of track failure. If this is not true then Table 4-4 only designates the ground hazard activity stage for that ground hazard event but may affect the ground hazard activity stage for the subsequent ground hazard in the FMEA.

In a number of railway ground hazard scenarios identified in this thesis, several ground hazard events have to occur in series before an ultimate ground hazard event can affect track failure. In these circumstances, the previous ground hazard event becomes essentially a causal factor for the subsequent ground hazard event. If a lag time is identified or the ground hazard event is insufficient to trigger the next ground hazard event in the series the preceding ground hazard event is a preparatory causal factor. If there is no lag time identified, the preceding ground hazard becomes a trigger causal factor for the subsequent ground hazard event.

The generic descriptions of the four states of track stability states **1** to **4** stemming from all railway ground hazards are as follows.

A railway ground hazard is assessed as a ***4**, stable state*, if the margin of stability of the ground hazard system that can affect the track is sufficiently high to withstand all destabilizing processes. Railway ground hazards in this state are identified by the presence of ground condition causal factors but the absence of any significant process related causal factors. The ground hazard activity stages that correspond to this state for the ground hazard events that immediately precede track failure are:

- Abandoned, where the process causal factors of the activity are no longer apparent;
- Stabilized past one season, where artificial remedial measures have stopped the activity and more than one cycle of seasons has passed; and
- Relict, where there is only remnant evidence of previous activity and the process causal factors of the activity are no longer apparent.

A railway ground hazard is subjectively assessed as a ***3**, stable state – monitoring required*, if the margin of stability of the ground hazard system that can affect the track is once again sufficiently high to withstand all destabilizing processes. However in this case there are significant preparatory process causal factors present to warrant periodic monitoring of the site. The ground hazard activity stages that correspond to this state for the ground hazard events that immediately precede track failure are:

4. Preparatory, where no activity has occurred but preparatory process causal factors are apparent;
5. Stabilized recently, where artificial remedial measures have stopped the activity but less than one cycle of seasons has passed; and
6. Dormant, where the causes of the activity remain apparent, but last moved more than one annual cycle of seasons ago.

A railway ground hazard is subjectively assessed as a ***2**, marginally stable state*, if the ground hazard system that can affect the track will fail at some time in response to destabilizing processes attaining certain levels. Certain levels for ground hazards refer to predetermined rates and volumes of activity dependent predominantly on the mode of track failure as defined in Section 4.6.1. This state is subjectively assessed if there are triggering causal factors identified that can make the track actively unstable. The ground hazard activity stages that correspond to this state for the ground hazard events that immediately precede track failure are:

- Marginal, where no activity has occurred but preparatory and triggering causal factors are apparent; and
- Suspended, ground hazards that have been active in the last annual cycle of seasons but are not moving at present.

A railway ground hazard is subjectively assessed as a ***1**, actively unstable state*, if destabilizing processes affecting the slope system that can affect the track have produced continuous or intermittent track failure by attaining certain levels. Certain levels for ground hazard hazards refer to predetermined rates and volumes of activity dependent predominantly on the mode of track failure as defined in Section 4.6.1. The ground hazard activity stages that correspond to this state for the ground hazard events that immediately precede track failure are:

- Active, ground hazard is currently active; and

- Reactivated, ground hazard is again active after being inactive.

Table 4-4 Proposed track stability states and ground hazard activity stages for railway ground hazard scenarios

Track Stability State		Ground hazard Activity Stage	
(4) Stable	Margin of stability of the ground hazard system that can affect the track is sufficiently high to withstand all destabilizing processes. Only ground condition causal factors apparent Absence of any significant process related causal factors.	**Abandoned**	Where the process causal factors of the activity are no longer apparent
		Stabilized past one season	Where artificial remedial measures have stopped the activity and more than one cycle of seasons has passed.
		Relict	Where there is only remnant evidence of a previous activity and the process causes of the activity are no longer apparent
(3) Stable-monitoring required	Margin of stability of the ground hazard system that can affect the track is sufficiently high to withstand all destabilizing processes. Preparatory process causal factors apparent but triggering causal factors can not make the track actively unstable	**Preparatory**	Where no activity has occurred but preparatory process causal factors are apparent
		Stabilized recently	Where artificial remedial measures have stopped the activity but less than one cycle of seasons has passed
		Dormant	Where the causes of the activity remain apparent but last moved more than one annual cycle of seasons ago
(2) Marginally Stable	Slopes that will fail at some time in response to destabilizing processes attaining certain levels dependent on the mode of track failure. Triggering causal factors identified that can make the track actively unstable	**Marginal**	Where no activity has occurred but preparatory and triggering causal factors are apparent
		Suspended	Ground hazards that have moved in the last annual cycle of seasons but are not active at present
(1) Actively Unstable	Processes affecting the ground hazard system have produced continuous or intermittent track failure by attaining certain levels dependent on the mode of track failure.	**Active**	Ground hazard that is currently active
		Reactivated	Ground hazard that is again active after being inactive

4.4.5.4 Application of GH Activity Stage and Track Stability State to Characterize Status of Railway Ground Hazard Scenarios

Ground hazard activity stages and track stability states, as defined in Table 4-4, are used to assess the status of a railway ground hazard scenario at a particular railway ground hazard location. Once the specific FMEA is mapped out for a particular railway ground hazard location, the activity stage of the individual hazard events are assessed, starting from the initiating event and moving down the event branches. The activity stage assessed for each hazard event affects the status of the next event as it represents either a preparatory or trigger causal factor for the next event. If the next event is another ground hazard event, the activity stage of that event is affected. If the event to the right is a track failure of a particular type the track stability state for that track failure type is affected as indicated in

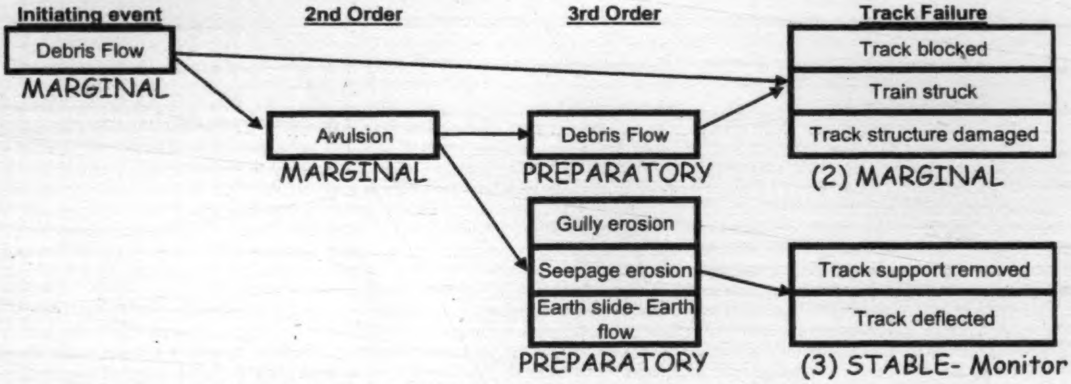
Table **4-4** 4-4. A hypothetical case example is used to illustrate the procedure to assess the current status of the entire railway ground hazard scenario at a given location.

Figure 4-3 depicts the FMEA for a Debris Flow-Avulsion-Debris Flow / Gully Erosion / Seepage Erosion / Earth Slide – Earth Flow hazard scenario taken from Section 7.2.1,. At this site, in May of the year, the upper catchment area where most of the channelized debris flows originate from has a significant accumulation of debris from rock falls, and 4 metres of snow have accumulated. Snow avalanches have filled the mid reach of the channel above the apex with dense snow and debris. Given that these preparatory causal factors exist, a trigger causal factor such as a rapid melt, an intense rain storm or a rain on snow event will very likely trigger a channelized debris flow. These factors infer that the initiating debris flow hazard is at a *marginal activity stage*. Because these debris flows can reach the track, the track stability state from this hazard is at ***(2) Marginally Stable***.

Below the apex of the debris cone, the pre-existing channel, incised by previous debris flows, is half full of debris and the right side of the cone has built up over the past 50 years such that the debris deposition is starting to favour the left side of the cone. Given that these preparatory causal factors exist, a trigger causal factor such as a debris flow, in combination with a subsequent torrent of water, is likely to result in an avulsion of the pre-existing stream channel and the uncontrolled debris and water flows will come to the track at a random location. These factors indicate that the secondary avulsion hazard is at a *marginal activity stage,* however since the avulsion cannot directly affect the track, it does not necessarily make the track marginally stable. It does represent a preparatory process causal factor for tertiary debris flows, gully erosion, seepage erosion, or earth slide-earth flows. However due to the presence of good ditches, numerous culverts, a wide shoulder on the downstream side of the track and the railway embankment constructed of large rock fill, no trigger causal factors are identified that could make the track actively unstable from the tertiary hazards. As the tertiary hazards remain in the *preparatory activity stage* the track stability from these hazards is in the ***(3) Stable-monitoring required*** state.

Debris Flow - Avulsion - Debris Flow/Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow **Count 31**

DFw - Av - DFw / GE / SE / ESl - EFw -


Initiating event
2nd Order
3rd Order
Track Failure
Debris Flow
MARGINAL
Avulsion
MARGINAL
Debris Flow
PREPARATORY
Track blocked
Train struck
Track structure damaged
(2) MARGINAL
Gully erosion
Seepage erosion
Earth slide- Earth flow
PREPARATORY
Track support removed
Track deflected
(3) STABLE- Monitor

Notes:
1. Primarily channelized debris flows from upstream of tracks
2. Avulsion results from debris redirecting or blocking water flow in channel, culvert or bridge
3. 3rd Order Debris flow results from new channel scour and entrainment from misdirected flow.
4. GE, SE or ESl-EFw result from misdirected water flow passing over/through the track grade

Figure 4-3 Illustration of the use of ground hazard activity states to estimate the state of track stability.

In summary, the track stability state is marginal due to the potential for debris flows directly affecting the track by blocking the track, striking a train or damaging a track structure. The track stability state is stable, but requires monitoring for avulsion causing either gully erosion, seepage erosion or an earth slide – earth flow at the track affecting the track by either removing support or deflecting it.

This exercise provides the following:

- A qualitative assessment of the likelihood of track failure.
- An indication of the most likely chain of events or branch of the FMEA most likely to cause track failure.
- The most likely type of track failure.
- A check list of ground condition and process causal factors to investigate as part of the monitoring program.

4.5 Railway Ground Hazard Causal Factors and Attributes

The intent of this section is to provide the initial framework for identification and description of causal factors and their associated attributes. Railway ground hazard causal factors are defined as conditions or processes that either prepare or trigger a railway ground hazard event. The expression of the causal factors (conditions or processes) at a given ground hazard location are referred to as *attributes*. Attributes are used as direct and indirect indicators of the existence and extent of an associated causal factor at a hazard site. In this section, causal factors and attributes are further defined and described, followed by a description of a quantitative attribute-based approach. Preliminary glossaries (listing and description) of railway ground hazard preparatory and trigger causal factors are proposed in the corresponding railway ground hazard classes in Chapters 6 through 12.

4.5.1 Railway Ground Hazards Causal Factors

Popescu (1994) and the author's experience indicates that can a landslide can rarely be attributed to a single causal factor. Varnes (1978) pointed out the process leading to the development of the landslide has its beginning with the formation of the rock itself, when its basic physical properties are determined, and includes all subsequent events of crustal movements, erosion, and weathering.

In many cases, it may be possible to identify a single triggering process, but the ultimate causes of the landslide or, in general, the railway ground hazard event involves a number of preparatory conditions and processes. Expanding on Popescu's (1994) suggested operational approach for classification of landslide causal factors to address railway ground hazards, it is first necessary to make a distinction between ground conditions and processes. Causal factors for railway ground hazards are subsequently subdivided into the following categories.

> Ground Conditions
>
> Ground condition causes include the material and mass characteristics of the ground that can be attributed as being part of the cause of the hazard. Expanding on Brunsden's (1979) definition, ground conditions are the specification of the railway ground hazard system, the setting on which a process can act to prepare or trigger a ground hazard event.

Geomorphological Processes

Geomorphological processes and changes that take place in the evolution of landforms.

Physical Processes

Physical process causal factors are changes brought on by natural external destabilizing forces from the natural environment around the ground hazard. They result primarily from climatic or hydrologic conditions but can also be the result of tectonic action, such as seismic activity or volcanism.

Man-made or Animal Processes

Manmade or animal process causal factors are changes brought on by actions of man or animal.

Note that ground conditions can only be preparatory causes whereas processes can be either preparatory or triggering. The following two sections provide further clarification of preparatory versus triggering causal factors.

4.5.1.1 Preparatory Causal Factors

In the context of railway ground hazards, preparatory causal factors are conditions or processes that make the ground hazard event more likely, without actually initiating it. If the ground hazard event can directly affect the track, the preparatory causal factor will tend to move the track from a stable to a marginally stable state. In essence, they are what cause the ground hazard to exist, but do not cause the event to occur.

Destabilizing processes, based on their temporal variability, may be grouped into slowly changing such as weathering, erosion or a rise in the phreatic surface and rapidly changing such as intense rain, rain-on-snow, earthquakes or draw-down. Attention is often focused on processes that invoke the greatest rate of change. Regardless they are still preparatory factors if they do not act immediately to cause the ground hazard event to occur. They may have incrementally brought the hazard closer to occurance but do not immediately cause the hazard event. For instance, train action, a preparatory factor, causes incremental plastic deformations of a weak sub-grade, a preparatory process ground condition causal factor, setting up a closed depression in the lower permeable and weaker sub-grade under the ballast, preparatory process causal factors. Subsequently, intense rainfall or significant antecedent rain, preparatory process factors, fill the depression, saturating non-cohesive fines or soften the weak clay sub-grade, preparatory process causal factors. These conditions and processes have set up the track for failure, created either an incremental plastic deformation hazard or incremental dynamic liquefaction hazard, but failure has not yet been triggered.

Preparatory causal factors are useful in the early identification of the ground hazard and in prevention of the ground hazard event by allowing focus on factors that have a significant influence on the potential track failure. Preparatory causal factors are utilized for ground hazard identification and both qualitative and quantitative risk assessments.

4.5.1.2 Triggering Causal Factors

The general requirement for a railway ground hazard triggering causal factor is that it initiates the railway ground hazard event. If a ground hazard event can directly affect track failure, the identification of a trigger causal factor for that event tends to move the track stability state from marginally stable to actively unstable. Wieczorek (1996) state that one definition of a trigger for landslides is an external stimulus (such as intense rainfall, earthquake shaking, volcanic eruption, storm waves, or rapid stream erosion) that causes a near-immediate response in the form of a landslide by rapidly increasing the stresses or by reducing the strength of slope material. However a number of landslides seem to occur without an apparent attributable trigger and are likely the result of a gradual change in preparatory causal factors that brings the slope to failure. Leroueil (2004) described triggering factors that led to failure and aggravating factors that produced a significant modification of stability conditions or of the rate of movement. These definitions of trigger causal factorsshare, as Wieczorek (1996) concluded, the requisite short interval between cause and effect. This is the prerequisite for identifying triggers used in this thesis and it is applied to all five Level II classes of Railway Ground Hazards. A further refinement of the definition of a trigger, in the context of railway ground hazards and risk, is that the trigger directly results in the ground hazard event. The summary definition of a *trigger* for railway ground hazards is thus *an external stimulus or change in preparatory causal factors that causes a near-immediate response in the form of a ground hazard event*. For instance, following the example from Section 4.5.1.1 for preparatory factors, finally *train action*, a trigger, causes dynamic liquefaction and large plastic deformations of the subgrade resulting in rapid subsidence of the track causing actual track failure. The track is now unsafe for trains at track speed. Trigger causal factors are utilized primarily for prediction, warning and assessment of the temporal frequency of the events.

4.5.2 Railway Ground Hazard Attributes

Attributes associated with causal factors for railway ground hazards are generally of two types.

1. Those that provide evidence of processes but generally do not participate in the process. This would include such evidence as:
    - Cracks
    - Localized displacements on vertical profiles.
    - Geometry and movements evidencing sliding of essentially rigid blocks
    - Colluvium
    - Contorted stream channel
    - Track deflections
    - Stream bank sloughs
    - Leaning or deformed trees
    - Collapse depressions
2. Those that are indirect indicators of causal factors, but may not be associated with activity. This would include evidence such as:
    - Landforms
    - Material types
    - Terrain parameters
    - Structural geology
    - Stream proximity
    - Seepage
    - Climatic records
    - Seismic zonation

Leroueil and Locat (1998) provide examples of revealing attributes for a reactivation of an earth slide in stiff clay and clay shale as follows:

1. Localized displacements on vertical profiles.
2. Geometry and movements evidencing sliding of essentially rigid blocks.

A railway case example of a similar landslide, at a similar stage, that exhibited these attributes, is illustrated in Figure 4-4. This case, from Mile 184 of the CN Rivers Subdivision, shows the first type of revealing attributes that provide evidence of movement, such as the pre-existing outline of the landslide and evidence that the track had to be moved up-slope in the past. At the time of the photo, the track was experiencing vertical and lateral deflection, indicating signs of retrogression.

Attributes of the second type that are indirect indicators that the preparatory factors exist include the colluvial river valley slope, the relative age of the slope since glaciation, the existence of near-surface clay shale in the area and perhaps the observation that the toe of the slope is on the outside meander of the river (off the photo).

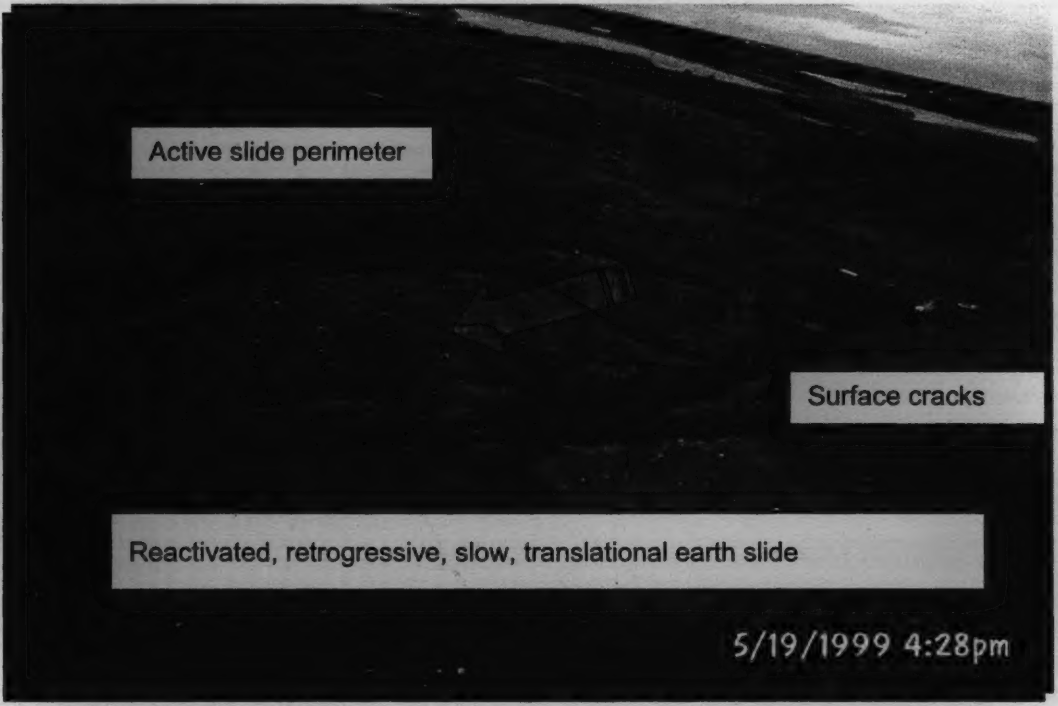


Figure 4-4 Example of attributes for a reactivated, retrogressive, slow, translational earth slide in stiff clay and clay shale. Mile 184 CN Rivers Subdivision (Photo by Tim Keegan).

Attributes are very useful for hazard identification, risk estimation, risk control and monitoring.

4.5.3 Quantitative Attribute-based Approach

To facilitate quantitative risk assessment of railway ground hazards, a quantitative attribute-based approach is suggested for calculating component event probabilities within the overall railway ground hazard risk assessment system (RGHRAS).

Quantitative attribute methods are a means of developing an inventory of causal factors (conditions and processes) and their associated attributes, that indicate a system is more or less likely to fail, and, using that inventory, to systematically assign a probability of failure within a quantitative risk assessment. One of the best-documented uses of attribute methods is that by Muhlbauer (2003) who developed the approach to improve decision-making for pipeline integrity management. BGC Engineering Ltd. uses the approach to rank the potential for pipeline failure resulting from ground hazard exposure (Savigny et al., 2002; Porter and Savigny, 2002; Porter et al., 2004; Esford et al., 2004). The BC Ministry of Transportation uses a similar semi-quantitative method to assess the risks from rock fall. The CN Rockfall Hazard and Risk Assessment (CNRHRA) system (Pritchard et al, 2005) and the developing CN River Attack Track Risk Assessment System (CNRATRAS), both developed under the direct supervision of the author, also use a quantitative attribute approach and thus set the ground work for application to all railway ground hazards.

The approach involves quantifying engineering judgement, by developing a set of attributes that provide an indication of probability of hazard occurrence and the probability of system failure, should the hazard occur. The possible responses for each attribute (e.g. slide volume, speed or mobility; stream classification; bank materials; or the presence of obstructions) are assigned numerical scores between 0 and 1 that are multiplied to provide an estimate of the probability of hazard occurrence.

Similarly, attributes relating to railway consequence likelihood (such as the distance between the stream and the railway) are assigned scores that are combined to provide an estimate of railway system vulnerability. The product of the probability of ground hazard occurrence and system vulnerability gives the estimated probability of railway consequences, such as track failure, service disruption or derailment. Once failure predictions are calibrated using failure statistics and engineering judgement, the results are sufficiently accurate to guide risk management activities such as the allocation of inspection, monitoring, and mitigation resources.

Use of quantitative attribute methods to assign event probabilities within a quantitative risk assessment offers several inherent advantages:

1. They provide an inventory and record of site conditions, and are thus ideal for tracking changes in conditions over time, meeting the requirement for a dynamic rating system;

2. They provide a more transparent and repeatable rating process since site attributes are easier to characterize in a systematic manner than are event probabilities; and,
3. The attribute response scores can provide a reasonable and defensible estimate of their influence on the probability of hazard occurrence or system vulnerability once calibrated using failure statistics, numerical modelling, and engineering judgement.

One of the efficiencies of using this approach is that only a select number of relevant factors are collected to complete the risk assessment. To apply this approach to other railway ground hazards it is thus advantageous to filter out a similar list of relevant causal factors and associated attributes necessary to ultimately complete the risk assessment.

4.6 Consequence Likelihood Factors

The author suggests that the three main consequences resulting from a railway ground hazard scenario are track failure, service disruption and, worst of all, derailment. A track failure has to occur before a service disruption or derailment consequence can follow. As well, these three consequences are not mutually exclusive, as they are often causes of each other. A track failure on its own represents a consequence, as losses are incurred to repair the track back to a safe condition. A track failure, if detected before a train encounters it, can still result in a service disruption in the form of a track closure or temporary slow order, both of which result in lost revenue and increased expenses, net income loss. If a track failure results in a train derailment, not only is the railway subject to personnel, property, liability and environmental losses, but the service disruption losses caused by the derailment usually increase exponentially. The probabilities that these consequences occur are referred to by the author as track vulnerability, service disruption vulnerability and derailment vulnerability. The following three sections describe these vulnerabilities and summarize the corresponding suggested causal factors and attributes necessary to qualify or quantify these probabilities.

4.6.1 Track vulnerability

Given that the ground hazard scenario occurs and in some way affects the track, the probability that a track failure will occur, as a result, is referred to as track vulnerability. In this section, the author better defines the modes of track failure and provide a preliminary list of factors required to characterize the track vulnerability. For clarity, the factors that influence track vulnerability exist within the track structure, which includes the track, ballast, sub-ballast, embankment, overhead structure or supporting structure, and the train clearance envelope. In Table 4-5, the author proposes a description of each of the track failure modes and lists the corresponding railway ground hazards that can result in them.

Table 4-5 Summary of track failure modes and causative ground hazards.

Modes of Track Failure *…. ground hazards may cause a track failure by:*	**Description**	**Causative Ground Hazards**
Removing support from the track structure;	Ground beneath the track is removed or compromised such that the track can no longer safely support train loading at design speed.	• Rock slides, topples • Debris slides • Earth slides, spreads, flows • Settlement, Collapse • Gully erosion, Seepage erosion, piping, dissolution • Sub-aqueous flow erosion
Blocking the track;	Sufficient material of the appropriate characteristics and spatial distribution occupy the train clearance envelope such that trains can no longer pass safely at design speed.	• Rock falls, slides • Debris falls, slides, flows • Earth slides, spreads, flows • Channel aggradation • Snow avalanches • Surface Icing
Striking a train;	Sufficient material of the appropriate characteristics moving at sufficient speed and trajectory can damage the train equipment, derail the train or strike personnel such that trains can no longer pass safely at design speed.	• Rock falls, slides • Debris falls, slides, flows • Earth slides, flows • Snow avalanches
Deflecting the track rail surface,	A warp or twist of the track rail surface introduces a derailment potential whereby the flange of the rail car wheel can climb the rail due to the rigidity of the rail car and derail	• Rock falls, slides, topples • Earth slides, spreads, flows • Settlement, Collapse
Changing the track gauge	Opening or closing the track gauge introduces a derailment potential whereby the wheel can either climb the rail or fall off the rail surface.	• Rock falls • Debris falls, slides, flows
Damaging the track components or	Damage to any of the track structural components such as the tie, tie plates, clips, rails or joints introduces a derailment potential whereby the structural integrity of the track system is insufficient to support train loading at design speeds.	• Rock falls • Debris falls, slides, flows
Damaging track structures (such as bridges, retaining walls or sheds)	Damage to a track structure that either protects the track from the side or above (catch nets, barrier walls, protection sheds) or supports the track (bridges, retaining walls, culverts) introduces a derailment potential whereby the integrity of the track system is insufficient to protect or support trains at design speeds.	• Rock falls • Debris falls, slides, flows

Table 4-6 expands on Table 4-5 by providing a preliminary listing of the track vulnerability factors that have a bearing on the likelihood or avoidance of track failure corresponding to each mode of track failure.

Table 4-6 Listing of the track failure attributes corresponding to the modes of track failure and causative ground hazards.

Modes of Track Failure *.... ground hazards may cause a track failure by:*	**Track Vulnerability Factors**
Removing support from the track structure;	• Presence of retaining structures or bridges • Size, gradation and compaction of subgrade material. • Shoulder width • Ballast, sub ballast quality • Presence of revetment • Track drainage
Blocking the track;	• Ability to retain material (barrier walls, catch fences, ditch catchment, deflection berms) • Ability for material to pass over or under tracks (bridges, culverts, flumes, sheds) • Ditch catchment • Particle size, volume and distribution of material blocking track
Striking a train;	• Ability to retain material (barrier walls, catch fences, ditch catchment, deflection berm) • Ability for material to pass over or under tracks (bridges, culverts, flumes, sheds) • Ditch catchment
Deflecting the track rail surface,	• Track geometry (curves and spirals are more susceptible) • Train loading • Track surface • Shoulder width • Ballast, sub ballast quality
Changing the track gauge	• Track quality
Damaging the track components	• Continuous welded vs. jointed rail • Concrete vs timber ties
Damaging track structures (such as bridges, retaining walls or sheds)	• Location, shape, orientation, and foundation type of bridge piers and abutments. • Type of retaining wall (Tie-back, cantilever, gravity) • Location, shape, orientation, capacity, abrasion protection and foundation type of rock or snow sheds.

4.6.2 Service Disruption Vulnerability

Given that the ground hazard scenario occurs and track failure has occurred, the probability that there is a corresponding significant service disruption is referred to as the service disruption vulnerability. Factors that have a bearing on the service disruption vulnerability resulting from a track failure are summarized in Table 4-7.

Table 4-7 Summary of service disruption vulnerability factors

Service Disruption Avoidance Factor	Description
Train speed	The higher the speed the more likely the track failure can result in a significant speed reduction.
Warning devices and patrols	Absence of warning devices or patrols increases likelihood that train service is interrupted, as trains may have to travel at reduced speeds if climatic or seismic operational criteria are exceeded on entire territories. Conversely a fail-safe warning device may produce unnecessary service disruptions from *false-positives.
Siding or double track	A second track at the ground hazard site represents a possible bypass route and avoidance of the service disruption.
Train traffic frequency	The lower the frequency of train traffic, the lower the likelihood of a service disruption
Speed of track failure	The slower the track failure, the less likely a service disruption will ensue, as there is time for early detection and mitigation
Derailment	Service disruption is greatly increased if a derailment occurs as a result of the track failure.

* False positives refer to detector activations that are not the result of track failures

4.6.3 Derailment Vulnerability

Given that the ground hazard scenario occurs and track failure has occurred, the probability that there will be a derailment is referred to as the derailment vulnerability. Factors that have a bearing on the derailment vulnerability are summarized in Table 4-8.

Table 4-8 Summary of derailment vulnerability factors

Derailment Vulnerability Factors	Description
Train speed	The higher the train speed at a given location the longer the stopping distance decreasing the likelihood that a train can stop short of a visible track failure.
Track Gradient	The more negative the track gradient at a given location the longer the stopping distance decreasing the likelihood a train can stop short of a visible track failure.
Track geometry	A warp or twist of the track rail surface introduces a derailment potential whereby the flange of the rail car wheel can climb the rail due to the rigidity of the rail car and derail. The derailment potential is increased significantly by higher curvature of the track. Also, the line-of-sight is reduced on curves, which reduces the time available for a train to react to a visible track failure.
Warning devices and patrols	Warning devices or track patrols can significantly reduce derailment likelihood by warning the train of a track failure.
Train traffic frequency	The lower the frequency of train traffic the lower the likelihood a train will encounter a track failure and derail
Speed of track failure	The faster the track failure the higher the likelihood a track failure will not be discovered before it is encountered by a train

4.7 Severity

The final requirement for the risk analysis is to estimate the severity of loss associated with each possible consequence, namely track failure, service disruption or derailment. The main measures of severity or loss associated with each of the railway consequences are summarized in Table 4-9.

It is apparent from Table 4-9 that the highest severity of loss from railway ground hazards results from a derailment consequence, especially when considering that a derailment will cause a significant higher service disruption than if there was no derailment.

Models used to estimate severity associated with a given railway ground hazard scenario range from the simplest form of model involving inputs expressed qualitatively to the more sophisticated severity models which may use inputs expressed quantitatively. The following sections describe a simple qualitative model used in the CN RHRA system (Pritchard et al, 2005) followed by a more rigorous, semi-quantitative model suggested by the author.

Table 4-9 Measures of severity associated with railway ground hazard consequences

Railway Ground Hazard Consequence	**Areas of Loss Associated with the Consequence**
Track failure	• Repair costs (labour, material, equipment)
Service disruption	• Net Income loss o Refers to the loss in net income, the total of revenue losses plus additional expenses resulting from the service disruption. o The unit for train delays is cost per train per hour of delay. This measure is highly variable and very difficult to determine (rough estimates range from \$25 to \$1250 Cdn./train/hr) o Late fines paid out to customers o Rerouting costs
Derailment	• Personnel/public loss (safety) o Refers to well being of train crew as well as any public that are affected by the train derailment o Refers to well being of the travelling public on passenger trains (i.e. The Hinton Crash 1988) o Includes illness, injury or fatality • Repair and clean up loss o Labour, material and equipment costs expended to repair the tracks and clean up the derailment site. • Property loss o Includes loss of any assets owned by the railway (i.e.) locomotives, cars, rail, slide fences, detection devices, structures, and facilities o Also includes commodities being shipped and compensation fines for the loss or damage of goods • Liability loss o Arising from torts, statutes, and criminal law o Consequences more severe if derailment occurs in sensitive areas such as Provincial Parks, First Nations Reserves, and municipalities o Indirect effects of liability losses include a tarnished public image and a loss in market share, however this loss is difficult to quantify • Environmental loss o Refers to leakage of dangerous and/or toxic commodities around the track which could seep into local waterways, and affect vegetation or wildlife in the area o Downstream usage of water for uses such as drinking water/industrial purposes may have to be shut down resulting in large fines and clean-up costs

4.7.1 CNRHRA Consequence Factor Model

Because the CN RHRA rating is used as a relative risk measure used to prioritize mitigation and monitoring activities, severity of derailment is qualitatively assessed. The assessment uses site-specific parameters (Pritchard et al, 2005) such as:

- Proximity to water,
- Distance between the track and track embankment crest,
- The presence of railway or other infrastructure (tunnels, bridges, highways, dwellings), and
- The likelihood that cargo would reach the water body.

These factors are used to determine a qualitative derailment consequence category used to weight the derailment risk rating according to the likely severity of a derailment. These four consequence categories presented in Table 4-10 are each subjectively assigned a numeric value between 0 and 1.0 with 1.0 being the most severe.

Table 4-10 CNRHRA consequence categories for train derailment (Pritchard et al, 2005)

Category	Description
A	Flat ground, low environmental impact
B	Low chance cars will reach water or infrastructure
C	Moderate chance cars will reach water or infrastructure
D	Close to slope crest, cars likely to reach water or infrastructure

4.7.2 Derailment Severity Model

In this section the author proposes a more detailed derailment severity model. The purpose of this derailment severity model is to create a tool by which management can gauge the severity of a potential derailment at a particular mileage. Combined with the product of the railway ground hazard scenario probability, the track vulnerability and the derailment vulnerability at a corresponding mileage, a quantitative relative risk score can be obtained. The model attempts to systematically consider all relevant site-specific factors and the combination of the considerations to estimate the relative severity of the various loss types associated with derailments listed in Table 4-9.

The data used to create the severity model comes from CN's Easymap Geographic Information System (CN GIS, 2004) that stores administrative, terrain, biophysical and infrastructure information. The data collected from these maps can be organized into three groups:

1. Point features

   Recorded for 0.05 mile increments which indicate the presence of the following:

   - Administrative
     - Agricultural Land Reserve (ALR)
     - Municipality
     - Provincial Park
     - First Nations Reserve
   - Biophysical
     - Stream
   - Infrastructure
     - Bridge
     - Culvert
     - Road crossing
     - Tunnel
     - Special Features (i.e.) bungalows, signals, switches

2. Digital elevation data

   Recorded for every 0.05-mile and up to 30 m on each side of the track, at 5m intervals.

3. Presence of a water body

   A 5 to 40m radius out from the track was considered, in increments of 5m (listed for every 0.05-mile).

A score quantifies each piece of information and therefore each 0.05-mile increment of track is assigned a total severity rating based on the presence of the features listed above. These severity ratings are then plotted against track mileage, which results in graphs that indicate the relative severity of each of the five loss types from a potential derailment and how it fluctuates along the track.

Admittedly, it is impossible to predict exactly what will happen in a derailment. Since so many factors can play a part, there are endless possibilities of how the train will derail. This model assumes the worst-case scenarios, thus the severity ratings could be higher than the actual consequences of most typical derailments.

In order to compare severity ratings across different mileages, the following assumptions were made:

- A train with the following aspects was considered in all cases:

    - one locomotive engineer and one conductor present
    - 2 locomotives
    - 90 cars
    - dangerous commodities are present

- Most or all of the dangerous goods present would leak into the surrounding environment.
- The train crew would not have warning of the potential cause of the derailment (i.e.) even if there were protective measures in place such as ground hazard detectors, it is assumed that they were not working or that the information was not relayed in time.

For the purposes of this model, severity ratings are set higher than the potential severities of most typical derailments because the worst-case scenario is assumed. For example, the model assumes that if a hazard such as a bridge existed, then a derailment on the bridge would leave the front end of the train (up to a maximum of 20 cars) in the river, while in reality this is not certain. Because the worst-case assumption is applied systematically, the severity ratings are, as a minimum, useful as a relative measure for comparison or prioritization exercises.

To develop and test the severity model a test section from Mile 50 to 60 of CN's Ashcroft Subdivision was chosen. This section was selected because it is representative of an area where a derailment could incur significant consequences. Features include close proximity to the Thompson River, numerous rock, debris and earth landslides and hydraulic erosion hazards, First Nation Reserves, and numerous railway infrastructure features (bridges, culverts, tunnels, signals).

Most derailments incur losses in more than one of the categories listed in Table 4-9 so for each 0.05 mile track segment a separate score is assigned in *each* of the five categories. For example, the presence of a bridge could lead to safety, property, liability, environmental and income losses. Assuming the worst-case scenario, the front end of the train used in this model would derail off the bridge into the river and the events listed in Table 4-11 could occur under each category of loss.

Table 4-11 Potential Losses Due to Presence of a Bridge

	Safety	**Property**	**Liability**	**Environmental**	**Net Income**
Type of Loss	Fatalities, serious injuries to crew and public passers-bys	Damages and/or lost assets – bridge, locomotives, cars, etc.	Fines and/or lawsuits due to damages and contamination	Dangerous commodities seeping into the river	Total of Revenue losses and expenses from derailment and service disruption

As shown in Table 4-11, a derailment on a bridge could result in a wide variety of effects in different areas, hence the importance of creating separate categories of loss. According to Cameron and Tweedale (1991), it is appropriate to consider the effects of an event by type before combining them to obtain a total relative risk score.

4.7.2.1 Determination of Severity Scores

The following sections describe the methodology used in the derailment severity model and present some preliminary results from the test section.

4.7.2.1.1 Point Features

All of the raw data is stored in an Excel spreadsheet and the presence or absence of a specific feature is indicated by a one and zero respectively. If there is more than one feature in a 0.05-mile increment of track, for example, 2 culverts, then the quantity of the feature is displayed. The values for the point features are multiplied by a weighting factor depending on the type of loss being considered. The scale of weighting factors was intentionally chosen to be simple at this preliminary stage as this is primarily an exercise to test the model and to compare severities in a relative manner. Further calibration against actual loss information is the next step in the development of the model and is recommended for future work beyond this thesis.

The range of possible weighting factors is listed in Table 4-13 and the weighting factors subjectively assigned to the point features are listed in Table 4-14. An explanation of why certain point features were assigned a specific weighting in one area of loss is also provided in Table 4-14.

Table 4-12 Range of Weighting Factors

Weighting Factor	Extent of Effect for a Specific Type of Loss
0.0	Not applicable
0.5	Moderate
1.0	Strong

Table 4-13 Point feature-weighting factors according to the type of loss

Feature	Safety	Property	Liability	Environmental	Net Income
ALR	0.5	0	1.0	1.0	0.5
	Possible exposure to public.	N/A	Action from private landowners, prov., etc.	Agriculture/valuable land affected by hazardous spills.	Track would normally be closed for more than 8 hours.
Municipality	1.0	0	1.0	0.5	0.5
	Probable exposure to public.	N/A	Action from private sector and province.	Harmful effects on local env.	Track would normally be closed for more than 8 hours
Park	0.5	0	1.0	1.0	0.5
	Possible exposure to public.	N/A	Action from province.	Potential harmful effects on protected areas.	Track would normally be closed for more than 8 hours
First Nations	0.5	0	1.0	0.5	1.0
	Possible exposure to public.	N/A	Action from First Nations.	Potential harmful effects on protected areas.	Possible service disruption –road blockades, etc.
Water body	1.0	1.0	0.5	1.0	0.5
	High risk for train crew	Loss of equipment	Action from province.	Hazardous goods leaking into the waterway.	Track would normally be closed for more than 8 hours
Bridge	1.0	1.0	0.5	1.0	1.0
	High risk for train crew.	Loss of equipment and/or structures.	Action from government.	Potential spills into the river.	Major service disruption for more than 24 hours.
Culvert	0	0.5	0.5	1.0	0.5
	N/A	Potential for damaged structures.	N/A	Potential blockage or seepage into waterways.	Track would normally be closed for more than 8 hours
Road crossing	1.0	0.5	1.0	0	1.0
	Probable exposure to public.	Potential for damaged structures	Private lawsuits or action from gov.	N/A	Major service disruption if public was involved. more than 24 hours
Tunnel	1.0	1.0	0	0.5	1.0
	High risk for train crew – limited access.	Potential for damaged structures and equipment.	N/A	Potential concentration of materials in tunnel.	Major service disruption due to limited access. more than 24 hours
Signal Bungalow	0.5	1.0	0	0	0.5
	Possible exposure to operating crew.	Potential for damaged structures and equipment	N/A	N/A	Track would normally be closed more than 8 hours
Signal	0.5	1.0	0	0	1.0
	Damage to signals could lead to other accidents.	Potential for damaged structures and equipment	N/A	N/A	Major service disruption due to signal reparation. more than 24 hours
Switch	0	1.0	0	0	1.0
	N/A	Potential for damaged structures and equipment	N/A	N/A	Longer service disruption due to switch replacement/repair. more than 24 hours

Feature	Safety	Property	Liability	Environmental	Net Income
Total Possible Score	7.5	7	6.5	6.5	9

4.7.2.1.2 Digital Elevation Model Data

Elevation data were used to calculate the slopes left and right of the track up to 30m on each side. Based on author's experience of several derailments, It was subjectively determined that a critical downhill slope of 1:1.25 (-39° - vertical: horizontal) would be used as a reference when setting the weighting factors. For the elevation data, the same weighting factors were used for each category of loss. This is because a steeper slope would result in graver consequences in all aspects. For example:

- Injuries and fatalities are more likely,
- Railway assets would be more severely impacted
- Opportunities for liability are increased,
- Hazardous spills could extend farther, and
- The overall service disruption and recovery losses would be greater.

The weighting factors for slopes are listed in Table 4-15.

Table 4-14 Slope weighting factors in the instance of a derailment.

Slope (S) Ratio Limits	Slope (S) Angle Limits	Weighting Factor
S<-1:1.25	S<-39°	1.0
-1:1.75<S<-1:1.25	-39°<S<-30°	0.5
S>-1:1.75	S>-30°	0

4.7.2.1.3 Proximity to Water Body

The proximity of a water body (river or lake) was recorded beside the tracks at increments of 5m up to a maximum radius of 40m. The presence and absence of a water body within a certain radius was indicated by a one or zero respectively. For every 5 metre increment away from the tracks within 5 to 20 metres, in which the water body encroaches, a weighting factor of one is assigned making a total possible score of 4, if the water body is within 5 metres of the track. For every 5 metre increment away from the tracks within 25 to 40 metres in which the water body has encroached a weighting factor of 0.5 is assigned making a total possible score of 2 if the water body is within 20 to 25 metres of the track. Just as with slope data, the weighting factors used for the water body data were the same in each category of loss, given that all types of loss would be aggravated if a derailment happened to occur close to a water body. The highest total score for Proximity to a water body is therefore six.

4.7.3 Results

The total severity score for each of the five categories of loss are presented in Table 4-16. Figure 4-5 to Figure 4-9 present the preliminary results from the derailment severity model for the five categories for the Ashcroft Mile 50 to 60 test section. Superimposed on the charts is the location of the known ground hazards along this section. Not shown is river erosion hazards that are known to exist along the entire section.

Table 4-15 Summary of total severity weighting scores for the five categories of loss from derailment

Source of Severity	Safety	Property	Liability	Environmental	Net Income	Total
Point Feature	7.5	7	6.5	6.5	9	36.5
Slope	1	1	1	1	1	5
Proximity to Water Body	6	6	6	6	6	30
Total	14.5	14	13.5	13.5	16	71.5

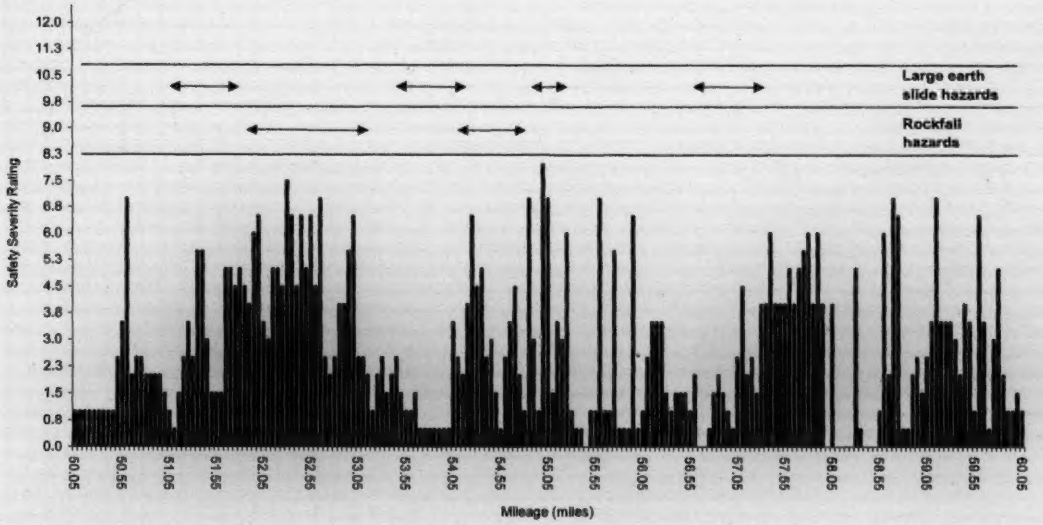


Figure 4-5 Safety loss severity score vs. track mileage

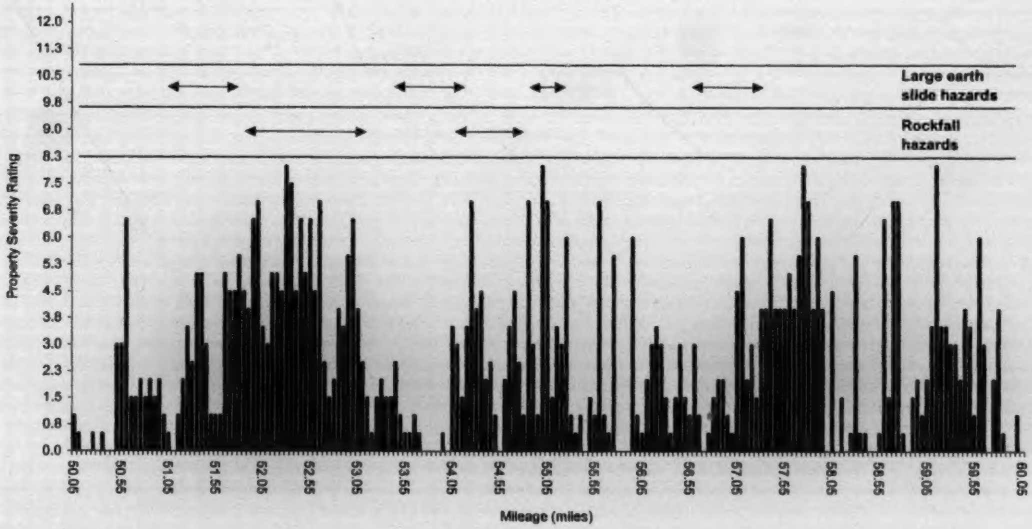


Figure 4-6 Property loss severity score vs. track mileage

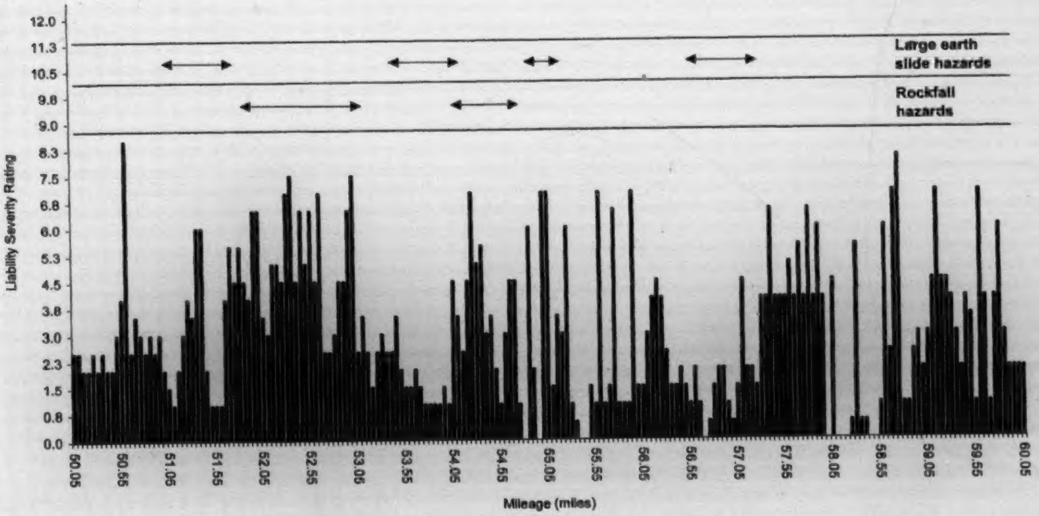


Figure 4-7 Liability loss severity score vs. track mileage

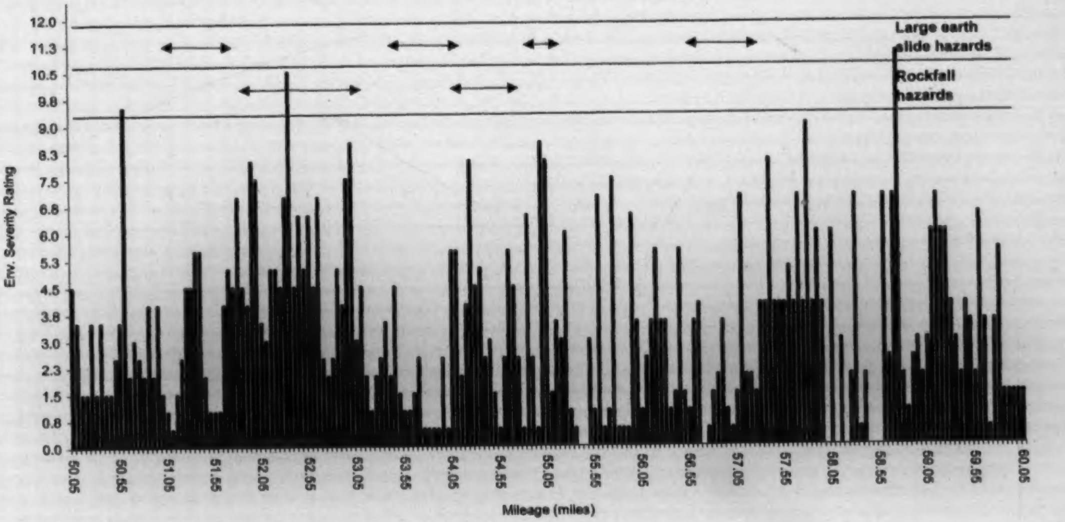


Figure 4-8 Environmental loss severity score vs. track mileage

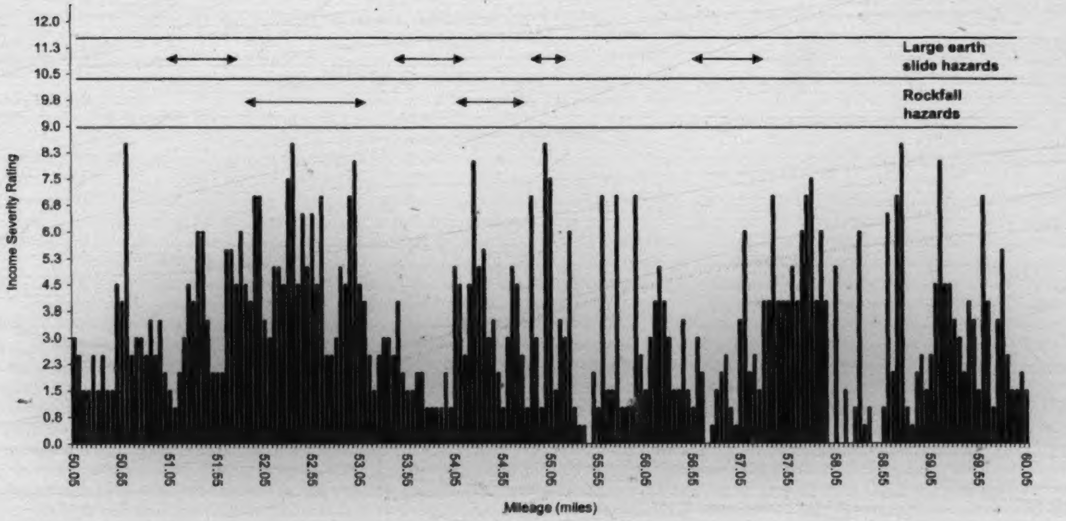


Figure 4-9 Income loss severity score vs. track mileage

Figure 4-10 presents the combined total score from all five loss categories. The highest possible total severity score from this model is 69.5.

These charts on their own represent a valuable screening tool to identify sections of track where a derailment is certainly unfavourable and draw attention to hazards in that section that now might warrant more attention. When these scores are combined with the estimated ground hazard scenario probability, track vulnerability and derailment vulnerability the resultant is a quantitative relative measure of ground hazard derailment risk for that section of track. The next refinement of this model, beyond the scope of this thesis, is to normalize the scores and calibrate the weightings to actual derailment loss records like those presented in Chapter 3 of this thesis.

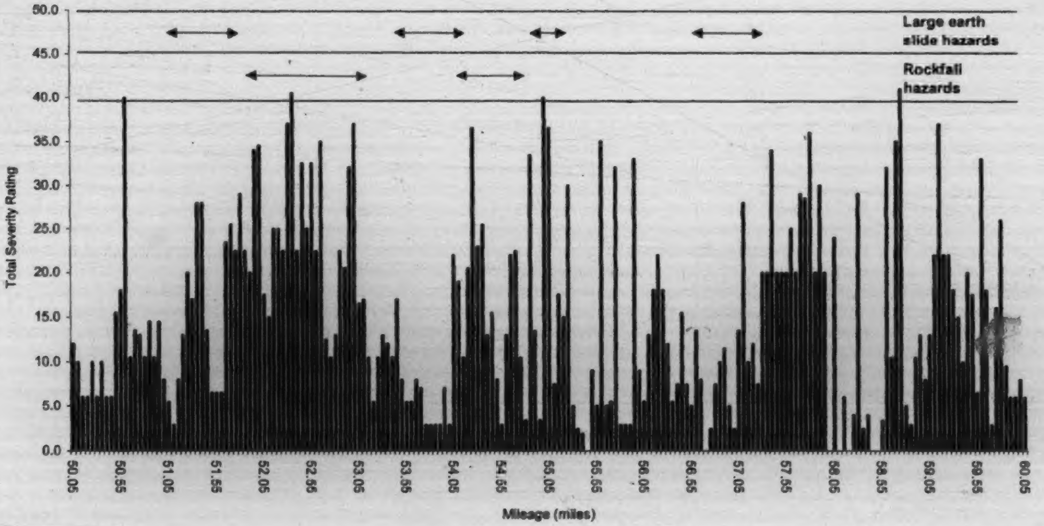


Figure 4-10 Total severity score vs. track mileage

4.8 Summary

Chapter 4 describes a methodology to systematically characterize railway ground hazard risk scenarios for use in risk management. A railway ground hazard risk scenario is comprised of a railway ground hazard scenario, track failure and consequences or loss to the railway. The product of the ground hazard scenario likelihood, the consequence likelihood and the severity is a measure of risk and thus the characterization methodology is structured similar to the risk equation. This information collected using this characterization methodology is intended to facilitate both qualitative and quantitative risk analysis.

The railway ground hazard scenario defined here maps the risk scenario from the initial hazard event through to track failure. A track failure occurs when the track ceases to be safe for train traffic at the posted track speed. Ground hazard events may result in a track failure by removing support from the track structure, blocking the track, striking a train, deflecting the track rail surface, changing the track gauge, damaging the track components or damaging track structures such as bridges or retaining walls.

Consequences to the railway are defined in terms of severity of track failure, service disruption or derailment.

The methodology developed to characterize railway ground hazard scenarios involves:

- Definition and characterization of the railway ground hazard scenario,
- Identification of railway ground hazard causal factors and attributes,
- Definition and characterization of consequence likelihood factors for track failure, service disruption and derailment consequences, and
- Suggestion and presentation of simple and more thorough methods to estimate the potential severity associated primarily with derailment consequences.

Realizing that the majority of railway ground hazard scenarios involve a combination of different ground hazard events that can happen in series or in parallel to result in different types of track failure, a failure mode and effect analysis (FMEA) is adopted to depict them. In conjunction with this, a nomenclature is suggested to name the railway ground hazard scenarios using the name of the individual ground hazard events with en dash (-) to denote series linkages and forward slash (/) to denote parallel linkages. The glossaries from Chapter 2 are used to represent the abbreviated form of the railway ground hazard scenario.

Identified as essential information to identifying and understanding the behaviour of ground hazards, different means to describe ground conditions and processes are suggested for each class of ground hazard. For landslide ground conditions and processes, the Cruden and Varnes (1996) landslide types and processes approach, is adopted. The unified soil classification system (Wagner, 1957) is adopted for more refined description of soils for landslides, subsidence and hydraulic erosion. Other important ground conditions identified include particle size distribution, spatial distribution of sediment sizes, both horizontally and vertically, non-cohesive versus cohesive, plasticity, sensitivity, preconsolidation and pore pressure distribution.

Rock material is characterized according to its relevant geological and physical conditions at site such as rock types, stratigraphy, discontinuities, seepage and weathering characteristics. Suggested methods for description of the overall rock mass character include the CSIR rating (Bieniawski, 1974) and the NGI (Barton, 1974) classification systems.

Processes involve primarily the kinematics of failure of the individual ground hazard event. For landslides, it is the type of movement of a mass of rock, debris or earth down a slope. For subsidence hazards it is a vertical displacement of the track associated with compression or displacement of materials in the track road bed. The subsidence processes are grouped according to the long-term rate of movement. Settlement is a slow or incremental process resulting from compression, consolidation, incremental plastic deformation or incremental dynamic liquefaction. Collapse is a sudden occurrence usually associated with vertical displacement into a void.

Processes of hydraulic erosion involve removal of soil particles or rock by the action of flowing waters. A description of the processes for each of the 15 identified railway hydraulic erosion hazards is provided in the classification of railway hydraulic erosion hazards from Chapter 2.

Three forms of ice commonly associated with railway icing hazards are listed. The Land Managers Guide to Snow Avalanche Hazards in Canada (CAA, 2002(b)) is suggested for the description of ground conditions and processes for snow avalanches.

To characterize the rates of system failure that can ultimately result in track failure within a railway ground hazard scenario it is required to estimate the typical rate and timing of the individual ground hazard events, which can be considered as components in the system, and the lag time that may exist between the hazard events.

The rate characterization can be a measure of either the continuous or cumulative incremental non-recoverable movements involved in the ground hazard event. The velocity scale proposed by Cruden and Varnes (1996) is adapted to measure predicted rates of railway ground hazard events excluding snow avalanches which uses CAA (2002(b)).

The timing of the ground hazard event corresponds to the timing of the primary trigger causal factors identified and assessed for the individual ground hazard event.

The lag time between the serial ground hazard events is identified as an essential parameter to estimate the rates of system failure within the railway ground hazard scenario.

The rate and timing of ground hazard events and the lag time between the events within the overall scenario has a direct bearing on the ability of the railway to react to the event to mitigate, protect or warn against track failure, service disruption or derailment. As well, understanding the rates and timing of hazard events and lag time between them, in the context of the mapped out railway ground hazard scenario, allows for the effective planning of monitoring and mitigation.

A key aspect in the characterization of the railway ground hazard risk scenario is to establish the status of a ground hazard within the identified ground hazard scenario and its relative effect on track failure. This provides the decision-maker with an invaluable indicator of how close the site may be to track failure and a prediction of what is likely to happen next. It also allows a correlation to the relevant controlling laws and parameters; preparatory and triggering causal factors; and the type of track failure.

A review of three suggested methodologies to categorize either the state of stability or the stage of movement of a landslide system by Popescu (1994), Cruden and Varnes (1996) and Lerouiel et al (1996), are used to develop a combined criterion in the form of a matrix to correlate track stability states and movement stages for railway landslide hazard scenarios. The presence or absence of causal factors is introduced as a means of discerning the state of track stability. A parallel criterion is then developed to assess the state of track stability for all railway ground hazard scenarios involving a combination of landslide, subsidence, hydraulic erosion, snow avalanches and icing hazard events.

The generic criterion developed, subjectively assesses track stability states from railway ground hazard activity within a railway ground hazard scenario, using identified causal factors.

In many railway ground hazard scenarios, more than one ground hazard event has to occur in series before an ultimate ground hazard event can affect track failure. In these circumstances, the previous ground hazard event becomes a causal factor for the subsequent ground hazard event. If a lag time is identified or the ground hazard event is insufficient to trigger the next ground hazard event in the series, the preceding ground hazard event is a preparatory causal factor. If there is no lag time identified, the preceding ground hazard becomes a trigger causal factor for the subsequent ground hazard event.

The generic descriptions of the four states of track stability states **1** to **4** stemming from all railway ground hazards are as follows.

- ***(4) stable state***: the margin of stability of the ground hazard system that can affect the track is sufficiently high to withstand all destabilizing processes. Railway ground hazards in this state are identified by the presence of ground condition causal factors but the absence of any significant process related causal factors.

7. ***(3) stable state – monitoring required:*** the margin of stability of the ground hazard system that can affect the track is once again sufficiently high to withstand all destabilizing processes. However in this case there are significant preparatory process causal factors present to warrant periodic monitoring of the site.

- ***(2) marginally stable state***: the ground hazard system that can affect the track will fail at some time in response to destabilizing processes attaining certain levels. Certain levels for ground hazards refer to predetermined rates and volumes of activity dependent predominantly on the mode of track failure. This state is subjectively assessed if there are triggering causal factors identified that can make the track actively unstable.

- ***(1) actively unstable state:*** destabilizing processes affecting the slope system, that can affect the track, have produced continuous or intermittent track failure by attaining certain levels. Certain levels for ground hazard hazards refer to predetermined rates and volumes of activity dependent predominantly on the mode of track failure.

Ground hazard activity stages and track stability states are used to assess the status of a railway ground hazard scenario at a particular railway ground hazard location. This is done by assessing the activity stage of the individual hazard events in the FMEA starting with the initiating event and moving down the event branches. The activity stage assessed for each hazard event affects the status of the next event in series as it represents either a preparatory or trigger causal factor for the next event. If the next event is another ground hazard event, the activity stage of that event is affected. If the event to the right is a track failure of a particular type, the track stability state for that track failure type is affected as indicated in Table 4-5. A hypothetical case example of a

Debris Flow-Avulsion-Debris Flow / Gully Erosion / Seepage Erosion / Earth Slide – Earth Flow hazard scenario is used to illustrate how the assessment methodology is used to determine the current status of the entire railway ground hazard scenario at a given location.

An initial framework for identification and description of causal factors and their associated attributes is presented. Railway ground hazard causal factors are defined as conditions or processes that either prepare or trigger a railway ground hazard event. The expression of the causal factors (conditions or processes) at a given ground hazard location are referred to as *attributes*. Attributes are used as direct and indirect indicators of the existence and extent of an associated causal factor at a hazard site. Causal factors and attributes are further defined and described, followed by a description of a quantitative attribute-based approach.

Causal factors for railway ground hazards are subdivided into:

Ground Conditions: The specification of the railway ground hazard system, the setting on which a process can act to prepare or trigger a ground hazard event.

Geomorphological Processes: Refer to changes that take place in the evolution of landforms.

Physical Processes: Refer to changes brought on by natural external destabilizing forces from the natural environment around the ground hazard. They result primarily from climatic or hydrologic conditions but can also be the result of tectonic action such as seismic activity or volcanism.

Man-made or Animal Processes: Refers to changes brought on by actions of man or animal.

Ground conditions can only be preparatory causal factors whereas processes can be either preparatory or triggering.

Railway ground hazards preparatory causal factors are conditions or processes that make the ground hazard event more likely without actually initiating it. Preparatory causal factors are useful in the early identification of the ground hazard and in prevention of the ground hazard event by allowing focus on factors that have a significant influence on the potential track failure. Preparatory causal factors are utilized for ground hazard identification and both qualitative and quantitative risk assessments.

The general requirement for a railway ground hazard triggering causal factor is that it initiates the railway ground hazard event. A *trigger* for railway ground hazards is defined as an external stimulus or change in preparatory causal factors that causes a near-immediate response in the form of a ground hazard event. Trigger causal factors are utilized primarily for prediction, warning and assessment of the temporal frequency of the events.

To facilitate quantitative risk assessment of railway ground hazards a quantitative attribute-based approach is suggested for calculating component event probabilities within the overall railway ground hazard risk assessment system. The approach involves quantifying engineering judgement by developing a set of attributes that provide an indication of probability of hazard occurrence and the probability of system failure, should the hazard occur.

Use of quantitative attribute methods to assign event probabilities within a quantitative risk assessment, provides an inventory and record of site conditions for tracking changes in conditions over time, a more transparent and repeatable rating process; and a reasonable and defensible estimate of the probability of hazard occurrence or system vulnerability once calibrated using failure statistics, numerical modeling, and engineering judgment. An additional advantage to this approach is that only a select number of relevant factors are collected to complete the risk assessment.

The three main consequence types resulting from a railway ground hazard scenario are track failure, service disruption and derailment. The probabilities that these consequences occur are referred to by the author as track vulnerability, service disruption vulnerability and derailment vulnerability. Track vulnerability refers to the probability a track failure will occur, given that the ground hazard scenario occurs and in some way affects the track. The modes of track failure are better described and correlated to the causative ground hazard that usually causes each mode. Track vulnerability factors are then suggested for each mode of track failure for future use to qualify or quantify these probabilities.

Given that the ground hazard scenario occurs, and track failure has occurred, the probability that there is a corresponding significant service disruption is referred to as the service disruption vulnerability. Suggested factors that have a bearing on the service disruption vulnerability resulting from a track failure are listed and described.

Given that the ground hazard scenario occurs, and track failure has occurred, the probability that there is a derailment is referred to as the derailment vulnerability. Suggested factors that have a bearing on the derailment vulnerability are listed and described.

The final requirement for the risk analysis is to estimate the severity of loss associated with each possible consequence, namely track failure, service disruption or derailment. The suggested main measures of severity or loss associated with each of the railway consequences include repair costs associated with track failure consequences; net income loss associated with service disruption consequences; and personnel/public loss(safety), repair and cleanup loss, property loss, liability loss, and environmental loss associated with derailment consequences.

Models used to estimate severity associated with a given railway ground hazard scenario range from the simplest form of model, involving inputs expressed qualitatively, to the more sophisticated severity models which may use inputs expressed quantitatively. To illustrate this, a simple qualitative model used in the CN RHRA system (Pritchard et al, 2005) is presented followed by presentation of a more rigorous semi-quantitative model suggested by the author.

This methodology is applied in the remainder of this thesis to summarize the results from inspection by or under the supervision of the author of approximately 3,000 railway ground hazard sites in CN Western Canada and to complete the preliminary analysis of the predominant railway ground hazards as determined from these inspections (Chapters 5 to 12).

Chapter 5 Identification and Characterization of Railway Ground Hazards-CN Western Canada

5.1 Introduction

The remainder of this Thesis involves risk characterization of railway ground hazards and hazard scenarios identified in CN Western Canada by the author, utilizing the risk characterization of railway ground hazard scenarios methodology described in Chapter 4. This chapter describes the systematic process developed and employed by the author to populate the extensive database of identified Railway Ground Hazards in CN Western Canada, excluding the former BC Rail, over the time period 1996 to 2006. The railway ground hazard scenario for all railway ground hazard sites contained in the CN Western Canada database are then identified and categorized into forty distinct railway ground hazard scenarios. These forty scenarios are then grouped and presented by the initiating ground hazard event in the scenario, according to the Level II classification. The chapter closes with a description of the process used to characterize the identified railway ground hazard scenarios in CN Western Canada in Chapters 6 through 12, utilizing the methodology developed in Chapter 4.

Coupled with the results of Chapters 2, 3, 4 and 5, this chapter completes the requirements of Section 5.3.4 "Hazard Identification" of the CAN/CSA-Q850-97 Standard (CSA, 1997). The three subtasks under this section are as follows. The chapters from this thesis where the various aspects of these subtasks were dealt with are indicated in parentheses:

1. Undertake a structured and comprehensive consideration of known sources of hazard or initiating events (Chapter 3 and 5), usually identified by reviewing past accidents and losses (Chapter 3).
2. Brainstorming by a team (the author) that understands all aspects of the system under consideration. Led by the team leader, this includes following the structured list of hazards (Chapter 2) to identify how a hazard might lead to a risk (risk scenarios, Chapter 5).

3. A preliminary assignment of frequency and consequence to the risk scenarios (Chapter 3).

5.2 Initial Identification and characterization of Railway Ground Hazards- CN Western Canada

Identification and characterization of the railway ground hazards in CN Western Canada was accomplished through ten years of systematic inspections undertaken by, or under the direct supervision of, the author. Initial identification of the ground hazards contained in the database was achieved using a variety of means, including:

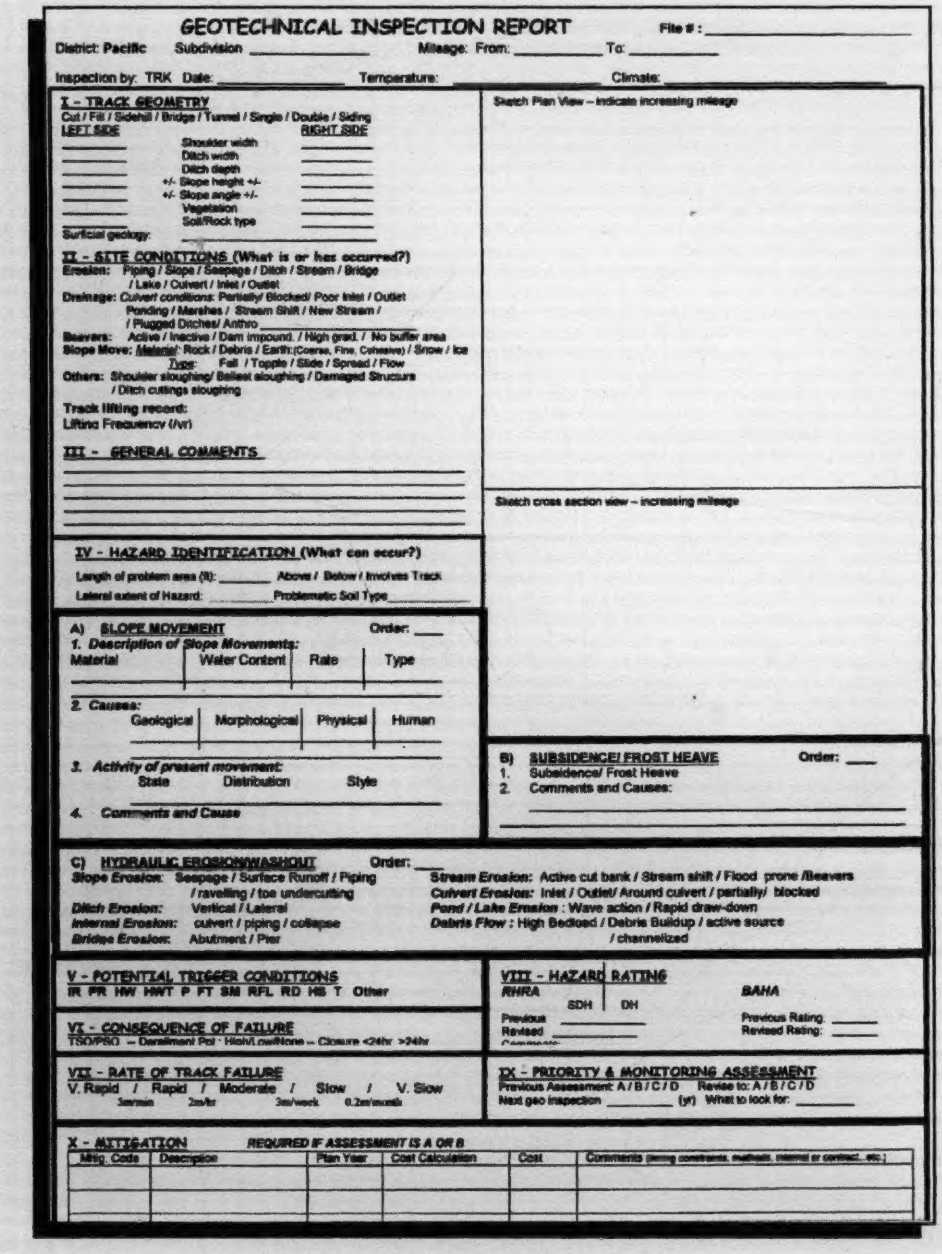
- Review of the loss records;
- Hi rail inspections by either track inspectors or geotechnical engineers;
- Train crew observations;
- 3rd party observations;
- Helicopter inspections;
- Incident reports;
- Maintenance records;
- Air photo analyses; or
- By inference (i.e. all rockslopes, cuts or natural, upslope of tracks or any river cut bank close to tracks is inferred to be a hazard location).

The inspections were completed using a standard inspection form developed by the author that is generally consistent with the Chapter 4 risk characterization methodology. The resulting database represents a comprehensive source of structured railway ground hazard information, used in this thesis to risk characterize CN's railway ground hazards in Western Canada.

5.2.1 The CN Geotechnical Inspection Report Form

To complete the structured and comprehensive consideration of known sources of hazard or initiating events and to facilitate the structured identification of railway ground hazards, the author, in 1997, started development of a standard geotechnical inspection report form (GIRF). The GIRF form has been used by the author to characterize all identified railway ground hazard sites in CN Western Canada. The resulting database was housed and maintained for CN on servers by Enkon Information Systems Ltd. located in Victoria, BC and the system was web based (Zorkin, 2005).

The geotechnical inspection report form is shown in Figure 5-2 and the corresponding glossary for the form is shown in Figure 5-3. The form is split into ten blocks as described in Table 5-1. Note that the development of this form predates the final version of the railway ground hazard classification (Chapter 2) and characterization (Chapter 4) systems, so the fields are not entirely consistent with the current system. Absent on the form is a specific selection of preparatory causal factors, however there are a significant number of fields that provide relevant information on preparatory causes which are used to compile a summary list of preparatory causal factors attributed to each hazard scenario. Also missing is a systematic classification of subsidence and hydraulic erosion hazards according to the author's current classification system presented in Chapter 2. These hazard scenarios are mapped out using other information contained in other fields on the form. As well, some of the fields were not consistently filled out, so the information in those fields is inconsistent and, in some circumstances, of little value. Commentary in Table 5-1 is included to draw a correlation between the fields collected on the GIRF and the classification and characterization systems presented in this Thesis.



GEOTECHNICAL INSPECTION REPORT File # : ____________

District: Pacific Subdivision ____________ Mileage: From: ________ To: ________

Inspection by: TRK Date: ____________ Temperature: ____________ Climate: ____________

I - TRACK GEOMETRY
Cut / Fill / Sidehill / Bridge / Tunnel / Single / Double / Siding

LEFT SIDE		RIGHT SIDE
______	Shoulder width	______
______	Ditch width	______
______	Ditch depth	______
______	+/- Slope height +/-	______
______	+/- Slope angle +/-	______
______	Vegetation	______
______	Soil/Rock type	______

Surficial geology: ____________

II - SITE CONDITIONS (What is or has occurred?)
Erosion: Piping / Slope / Seepage / Ditch / Stream / Bridge / Lake / Culvert / Inlet / Outlet
Drainage: Culvert conditions: Partially/ Blocked/ Poor Inlet / Outlet
Ponding / Marshes / Stream Shift / New Stream / / Plugged Ditches/ Anthro ____________
Beavers: Active / Inactive / Dam impound. / High grad. / No buffer area
Slope Move: Material: Rock / Debris / Earth:(Coarse, Fine, Cohesive) / Snow / Ice
Type: Fall / Topple / Slide / Spread / Flow
Others: Shoulder sloughing/ Ballast sloughing / Damaged Strucure / Ditch cuttings sloughing

Track lifting record:
Lifting Frequency (/yr)

III - GENERAL COMMENTS

Sketch Plan View – indicate increasing mileage

Sketch cross section view – increasing mileage

IV - HAZARD IDENTIFICATION (What can occur?)
Length of problem area (ft): ______ Above / Below / Involves Track
Lateral extent of Hazard: ______ Problematic Soil Type ______

A) SLOPE MOVEMENT Order: ___
1. Description of Slope Movements:

Material	Water Content	Rate	Type

2. Causes:

Geological	Morphological	Physical	Human

3. Activity of present movement:

State	Distribution	Style

4. Comments and Cause

B) SUBSIDENCE/ FROST HEAVE Order: ___
1. Subsidence/ Frost Heave
2. Comments and Causes:

C) HYDRAULIC EROSION/WASHOUT Order: ___
Slope Erosion: Seepage / Surface Runoff / Piping / ravelling / toe undercutting
Ditch Erosion: Vertical / Lateral
Internal Erosion: culvert / piping / collapse
Bridge Erosion: Abutment / Pier
Stream Erosion: Active cut bank / Stream shift / Flood prone /Beavers
Culvert Erosion: Inlet / Outlet/ Around culvert / partially/ blocked
Pond / Lake Erosion : Wave action / Rapid draw-down
Debris Flow : High Bedload / Debris Buildup / active source / channelized

V - POTENTIAL TRIGGER CONDITIONS
IR PR HW HWT P FT SM RFL RD HS T Other

VI - CONSEQUENCE OF FAILURE
TSO/PSO – Derailment Pot : High/Low/None – Closure <24hr >24hr

VII - RATE OF TRACK FAILURE
V. Rapid / Rapid / Moderate / Slow / V. Slow
3m/min 2m/hr 3m/week 0.2m/month

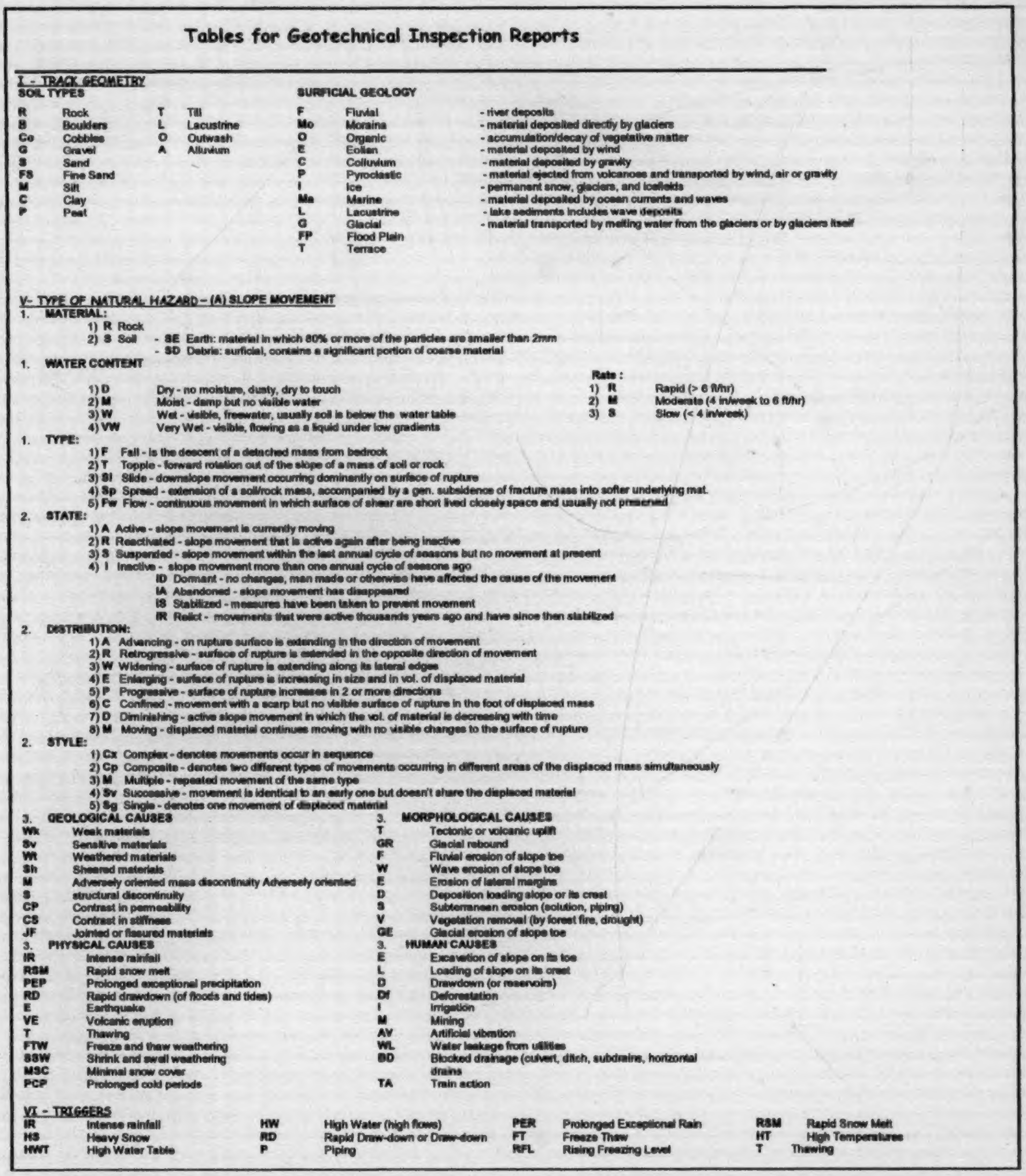
VIII - HAZARD RATING
RHRA
SDH | DH
Previous ____________
Revised ____________
BAHA
Previous Rating: ______
Revised Rating: ______

IX - PRIORITY & MONITORING ASSESSMENT
Previous Assessment: A / B / C / D Revise to: A / B / C / D
Next geo inspection ______ (yr) What to look for: ______

X - MITIGATION REQUIRED IF ASSESSMENT IS A OR B

Mitig. Code	Description	Plan Year	Cost Calculation	Cost	Comments (timing constraints, methods, internal or contract...etc.)

Figure 5-1 Keegan's geotechnical inspection reportform for railway ground hazard identification and characterization.



Tables for Geotechnical Inspection Reports

I - TRACK GEOMETRY

SOIL TYPES

R	Rock	**T**	Till
B	Boulders	**L**	Lacustrine
Co	Cobbles	**O**	Outwash
G	Gravel	**A**	Alluvium
S	Sand		
FS	Fine Sand		
M	Silt		
C	Clay		
P	Peat		

SURFICIAL GEOLOGY

F	Fluvial	- river deposits
Mo	Moraina	- material deposited directly by glaciers
O	Organic	- accumulation/decay of vegetative matter
E	Eolian	- material deposited by wind
C	Colluvium	- material deposited by gravity
P	Pyroclastic	- material ejected from volcanoes and transported by wind, air or gravity
I	Ice	- permanent snow, glaciers, and icefields
Ma	Marine	- material deposited by ocean currents and waves
L	Lacustrine	- lake sediments includes wave deposits
G	Glacial	- material transported by melting water from the glaciers or by glaciers itself
FP	Flood Plain	
T	Terrace	

V- TYPE OF NATURAL HAZARD – (A) SLOPE MOVEMENT

1. **MATERIAL:**
   - 1) **R** Rock
   - 2) **S** Soil - **SE** Earth: material in which 80% or more of the particles are smaller than 2mm
     - **SD** Debris: surficial, contains a significant portion of coarse material

1. **WATER CONTENT**

		Rate :		
1) **D**	Dry - no moisture, dusty, dry to touch	1)	**R**	Rapid (> 6 ft/hr)
2) **M**	Moist - damp but no visible water	2)	**M**	Moderate (4 in/week to 6 ft/hr)
3) **W**	Wet - visible, freewater, usually soil is below the water table	3)	**S**	Slow (< 4 in/week)
4) **VW**	Very Wet - visible, flowing as a liquid under low gradients			

1. **TYPE:**
   - 1) **F** Fall - is the descent of a detached mass from bedrock
   - 2) **T** Topple - forward rotation out of the slope of a mass of soil or rock
   - 3) **Sl** Slide - downslope movement occurring dominantly on surface of rupture
   - 4) **Sp** Spread - extension of a soil/rock mass, accompanied by a gen. subsidence of fracture mass into softer underlying mat.
   - 5) **Fw** Flow - continuous movement in which surface of shear are short lived closely space and usually not preserved

2. **STATE:**
   - 1) **A** Active - slope movement is currently moving
   - 2) **R** Reactivated - slope movement that is active again after being inactive
   - 3) **S** Suspended - slope movement within the last annual cycle of seasons but no movement at present
   - 4) **I** Inactive - slope movement more than one annual cycle of seasons ago
     - **ID** Dormant - no changes, man made or otherwise have affected the cause of the movement
     - **IA** Abandoned - slope movement has disappeared
     - **IS** Stabilized - measures have been taken to prevent movement
     - **IR** Relict - movements that were active thousands years ago and have since then stabilized

2. **DISTRIBUTION:**
   - 1) **A** Advancing - on rupture surface is extending in the direction of movement
   - 2) **R** Retrogressive - surface of rupture is extended in the opposite direction of movement
   - 3) **W** Widening - surface of rupture is extending along its lateral edges
   - 4) **E** Enlarging - surface of rupture is increasing in size and in vol. of displaced material
   - 5) **P** Progressive - surface of rupture increases in 2 or more directions
   - 6) **C** Confined - movement with a scarp but no visible surface of rupture in the foot of displaced mass
   - 7) **D** Diminishing - active slope movement in which the vol. of material is decreasing with time
   - 8) **M** Moving - displaced material continues moving with no visible changes to the surface of rupture

2. **STYLE:**
   - 1) **Cx** Complex - denotes movements occur in sequence
   - 2) **Cp** Composite - denotes two different types of movements occurring in different areas of the displaced mass simultaneously
   - 3) **M** Multiple - repeated movement of the same type
   - 4) **Sv** Successive - movement is identical to an early one but doesn't share the displaced material
   - 5) **Sg** Single - denotes one movement of displaced material

3.	**GEOLOGICAL CAUSES**	3.	**MORPHOLOGICAL CAUSES**
Wk	Weak materials	**T**	Tectonic or volcanic uplift
Sv	Sensitive materials	**GR**	Glacial rebound
Wt	Weathered materials	**F**	Fluvial erosion of slope toe
Sh	Sheared materials	**W**	Wave erosion of slope toe
M	Adversely oriented mass discontinuity Adversely oriented	**E**	Erosion of lateral margins
S	structural discontinuity	**D**	Deposition loading slope or its crest
CP	Contrast in permeability	**S**	Subterranean erosion (solution, piping)
CS	Contrast in stiffness	**V**	Vegetation removal (by forest fire, drought)
JF	Jointed or fissured materials	**GE**	Glacial erosion of slope toe
3.	**PHYSICAL CAUSES**	3.	**HUMAN CAUSES**
IR	Intense rainfall	**E**	Excavation of slope on its toe
RSM	Rapid snow melt	**L**	Loading of slope on its crest
PEP	Prolonged exceptional precipitation	**D**	Drawdown (or reservoirs)
RD	Rapid drawdown (of floods and tides)	**Df**	Deforestation
E	Earthquake	**I**	Irrigation
VE	Volcanic eruption	**M**	Mining
T	Thawing	**AV**	Artificial vibration
FTW	Freeze and thaw weathering	**WL**	Water leakage from utilities
SSW	Shrink and swell weathering	**BD**	Blocked drainage (culvert, ditch, subdrains, horizontal drains
MSC	Minimal snow cover		
PCP	Prolonged cold periods	**TA**	Train action

VI - TRIGGERS

IR	Intense rainfall	**HW**	High Water (high flows)	**PER**	Prolonged Exceptional Rain	**RSM**	Rapid Snow Melt
HS	Heavy Snow	**RD**	Rapid Draw-down or Draw-down	**FT**	Freeze Thaw	**HT**	High Temperatures
HWT	High Water Table	**P**	Piping	**RFL**	Rising Freezing Level	**T**	Thawing

Figure 5-2 Index sheet for Keegan's geotechnical inspection report form (refer to Figure 5-1)

Table 5-1 Description of the geotechnical inspection form. (Refer to Figure 5-2)

#	Section Title		Description
I	Track Geometry		Input of generic track and subgrade geometry and setting information.
II	Site Conditions		Input of observed site conditions at the time of the last site inspection. Space is provided to the right for a sketch plan and section of the site. Observed preparatory causal factors are noted here.
III	General Comments		Input of general free-form comments regarding the site at the time of the inspection.
IV	Hazard Identificaton *Systematic subjective assessment and characterization of the railway ground hazard*	Hazard Identification (general)	General information common to all hazard types. This collects the length of affected track, the relative position of the hazard, the lateral extent of the hazard away from the track and the difficult soil type involved, if known.
		Slope Movement Hazard	Describes a landslide hazard according to Cruden and Varnes (1996). Allows up to two material and movement types for description of complex landslides. Includes a comments and cause field for free form entries. The *Order* blank is provided to indicate the sequence of this ground hazard in a complex ground hazard scenario.
		Subsidence/ Frost Heave	Describes a track subsidence or frost heave hazard. Includes a comments and cause field for free-form entrees. The *Order* blank is provided to indicate the sequence of this ground hazard in a complex ground hazard scenario.
		Hydraulic Erosion /Washout	Describes a hydraulic erosion hazard. The *Order* blank is provided to indicate the sequence of this ground hazard in a complex ground hazard scenario.
V	Potential Trigger Conditions		Input of subjectively assessed potential trigger causal factors that can result in a near immediate response in the form of a hazard event.

#	Section Title	Description
VI	Consequence of Failure	Input of subjectively assessed that prescribed possible consequences given track failure occurs. Provides a cursory prediction of the likelihood and severity of track failure, service disruption or derailment.
VII	Rate of Track Failure	Input of subjectively assessed prescribed range of the rate of track failure resulting from the hazard scenario. Missing here is an indication of the type of track failure.
VIII	Hazard Rating	Input or revision of a Rockfall Hazard and Risk Assessment (RHRA) score or Beaver activity Hazard Assessment (BAHA) score if appropriate for the hazard.
IX	Priority and Monitoring Assessment	Input of subjectively determined prioritization and monitoring assessment. Refer to Figure 5-2 for explanation of A to D designation. This is somewhat consistent with the A to D stages of the railway ground hazard system failure introduced in Chapter 4.
X	Mitigation	Input of recommended mitigation details. Required if given an A or B priority.

5.2.2 Database of Railway Ground Hazards: CN Western Canada 1997-2005

In September 2005, the author downloaded approximately 1,300 of the most recent reports from each hazard location into an Excel© spreadsheet. Absent from this database is CN's rock fall hazard database which is contained within the CN rockfall hazard and risk assessment (CNRHRA) system (Pritchard et al, 2005). This system was supervised and administered by the author, but inspections are undertaken and the database was housed and maintained by BGC Engineering Inc., located in Vancouver BC (Pritchard, 2005).

The additional 1600 rock fall hazard records from CN Western Canada contained in the BGC CNRHRA database were also downloaded to the Excel© spread sheet with the information sorted into the appropriate fields. The total number of identified railway ground hazard records from CN Western Canada contained in the combined database amounted to slightly under 2,900. Using the functions in Excel© the records were subsequently reviewed and edited by the author to make the field entries consistent for analysis. The complete database of railway ground hazards in CN Western Canada are contained in an Excel© workbook entitled "Western Canada hazards Sept 27 2006.xls" available through Appendix B.

5.3 Identification and Categorization of the Railway Ground Hazard Scenarios: CN Western Canada

5.3.1 Introduction

From Section 4.3, there are five tasks to characterize the railway ground hazard scenario including a description of:

- The sequence of hazard events leading to track failure,
- Ground conditions,
- Processes,
- Rates, timing and lag time of railway ground hazard system failure, and
- Stages of railway ground hazard system failure.

In this section the author completes the first subtask in the characterization by identifying and categorizing the ground hazard scenarios for all railway ground hazard sites contained in the CN Western Canada database (Appendix C).

From Section 4.4, a railway ground hazard scenario is a sequence of ground hazard events that may lead to track failure. Using primarily the information contained in the records and supported by the author's familiarity with the sites, the railway ground hazard scenarios are mapped out for 2,791 of the approximate 2900 ground hazards identified using the nomenclature developed in Section 4.4.1. The remaining records had insufficient information to map ou the scenarios. The 40 railway ground hazard scenarios identified by the author are presented in the subsequent sections in a series of four tables (Table 5-2, Table 5-3, Table 5-4 and Table 5-5) grouped by the initiating ground hazard event in the scenario according to the Level II classification, namely Landslides, Subsidence, Hydraulic Erosion, and Snow and Ice. The intent of this section is to introduce an initial listing of the railway ground hazard scenarios. Each of the scenarios is systematically characterized using the methodology from Chapter 4 in subsequent chapters that make up the remainder of this thesis.

5.3.2 Landslide hazard scenarios: CN Western Canada

Table 5-2 presents all landslide hazard scenarios identified in the database, with the corresponding number of ground hazards assessed to have that scenario. Note that all rock fall hazards were identified from the RHRA system, which only identifies the ultimate ground hazard event, that being a rock fall. It is likely that a significant portion of these hazards are actually complex landslides such as rock slides – rock falls or rock topples – rock falls, but there is no consistent means to determine this from the current database. As well, the system assumes that any rock slope visible from the tracks presents a rock fall hazard, meaning that there is likely a disproportionate number of rock fall hazards identified, compared to other ground hazards which are not so easily identified such as piping or sub-aqueous erosion. Note the distinction under earth landslides between earth landslide hazards that affect earth embankments versus natural earth slopes.

Table 5-2 CN Western Canada landslide hazard scenarios

Level II Groups	Level III Subgroups	Ground Hazard Scenario	Coding	Count
Landslides	Rock Landslides	**Rock Landslides**		
		Rock Fall	RF -	1603
		Rock Slide	RSl -	7
			Subtotal	1610
	Debris Landslides	**Debris Landslides**		
		Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow	DFw - Av - GE / SE / ESl - EFw -	31
		Debris Fall	DF -	9
		Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall	DSl - SE / GE - DF -	2
		Debris Slide	DSl -	2
			Subtotal	44
	Earth Landslides	**Earth Landslides**		
		Earth(Embankment) Slide	E(Em)Sl -	90
		Earth Slide	ESl -	65
		Earth Slide - Earth Flow	ESl - EFw -	4
		Earth (Embankment) Slide - Earth Flow	E(Em)Sl - EFw -	4
		Earth (Embankment) Slide - Compression	E(Em)Sl - Cm -	4
		Earth Slide - Earth Fall	ESl - EF -	3
			Subtotal	170
	Total Landslide Scenario Hazards			1824

5.3.3 Subsidence hazard scenarios: CN Western Canada

Table 5-3 presents all Subsidence hazard scenarios identified in the database, with the corresponding number of ground hazards assessed to have that scenario. The subsidence hazard scenarios are further divided into the functional subgroups of subgrade plastic deformation, consolidation, compression, and sub-grade dynamic liquefaction. This division is based on common processes, attributes and initial hazard events. The scenarios are classified according to the initial ground hazard event(s) in the scenario and culminate with the ground hazard event that has the potential to affect the track, possibly causing track failure. Note that there were no scenarios investigated where a collapse hazard was identified as an initiating event. This does not, however, mean that these hazards do not exist as it is well known that burrowing animals, old timber, large uniform graded rock fill, underground mining etc. are common in, under and around railway embankments.

Table 5-3 CN Western Canada subsidence hazard scenarios

Level II Groups	Level III Subgroups	Ground Hazard Scenario	Coding	Count
Subsidence	Settlement	**Subgrade Plastic Deformation**		
		Subgrade Plastic Deformation	SPD -	13
		Subgrade Plastic Deformation – Earth(Embankment) Slide	SPD - E(Em)Sl -	7
			Subtotal	20
		Consolidation		
		Consolidation - Compression	Cn - Cm -	9
		Consolidation - Earth Spread	Cn - E(Pt)Sp -	4
		Consolidation	Cn - Cm(Pt) -	4
		Subtotal		17
		Compression		
		Compression	Cm -	13
			Subtotal	13
		Subgrade Dynamic Liquifaction		
		Subgrade Dynamic Liquifaction	SDL -	2
		Subgrade Dynamic Liquifaction - Earth Slide	SDL - ESl -	2
			Subtotal	4
	Total Subsidence Scenario Hazards			54

5.3.4 Hydraulic erosion hazard scenarios: CN Western Canada

Table 5-4 presents all hydraulic erosion hazard scenarios identified in the database, with the corresponding number of ground hazards assessed to have that scenario. The hydraulic erosion hazard scenarios are further divided into the functional subgroups of overland / through flow erosion, avulsion upstream of tracks, channelized flow erosion upstream of tracks, channelized flow erosion at bridge crossing, and wave erosion. This division is based on common processes, attributes, location relative to the track and initial hazard events. The scenarios are classified according to the initial ground hazard event(s) in the scenario and culminate with the ground hazard event that has the potential of affecting the track, possibly causing track failure.

Table 5-4 CN Western Canada hydraulic erosion hazard scenarios

Level		Ground Hazard Scenario	Coding	#
I	II			
Hydraulic Erosion	Overland / Through Flow Erosion	**Overland / Through Flow Erosion**		
		Seepage Erosion / Piping / Gully Erosin- Earth Slide / Culvert Failure / Piping Void Collapse	SE / P / GE - ESl - / CF / PD -	50
		Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide	SE / SW / GE - ESl -	46
		Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow	SE / SW / GE - SE / GE / - ESl - EFw -	24
		Seepage Erosion - Earth Slide - Earth Flow	SE - ESl - EFw -	12
		Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow	SE / GE - ESl - EFw -	12
		Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall	SE / SW / GE - DF -	7
			Subtotal	**151**
	Sub-aqueous Flow Erosion	**Avulsion Upstream of Tracks**		
		Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	Av(BH) - DFw / SE / GE / - ESl - EFw -	441
		Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	Av - DFw / SE / GE / - ESl - EFw -	28
			Subtotal	**469**
		Channelized Flow Erosion Parallel to Tracks		
		Local Scour / Bank Erosion - Earth Slide	LS / BE - ESl -	120
		Bank Erosion - Earth Slide	BE - ESl -	97
		Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide	LS / BE - SW / SE / GE - ESl -	18
		Bank Erosion / Avulsion - Earth Slide	BE / Av - ESl -	14
		Local Scour / General Scour / Channel Degradation - Earth Slide	LS / GS / ChD - ESl -	7
		Bank Erosion - Rock Slide	BE - RSl -	1
			Subtotal	**257**
		Channelized Flow Erosion Bridge Crossings		
		Channel Agradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion	ChA / DFw - Av - LS / SE / GE -	14
		Local Scour / General Scour / Bank Erosion / Avulsion	LS / GS / BE / Av -	6
		Local Scour / General Scour / Bank Erosion / Avulsion	GS / ChD - ESl -	2
			Subtotal	**22**
		Wave Erosion		
		Wave Erosion - Earth Slide -	WE - ESl -	3
			Subtotal	**3**
	Total Hydraulic Erosion Scenario Hazards			**902**

5.3.5 Snow and Ice hazard scenarios: CN Western Canada

Table 5-5 presents all snow and ice hazard scenarios identified in the database, with the corresponding number of ground hazards assessed to have that scenario. Note that at CN, snow avalanche hazard management is contracted to an outside firm, and as such, the ground hazard database does not contain the majority of the snow avalanche hazards. Similarly frost heave hazards are managed locally, and are thus not generally reported or tracked.

Table 5-5 CN Western Canada Snow and Ice hazard scenarios

Level II Groups	Level III Subgroups	Ground Hazard Scenario	Coding	Count
Snow and Ice	Snow Avalanche	**Snow Avalanches**		
		Snow Avalanche	SA -	3
			Subtotal	3
	Icing	**Icing**		
		Frost Heave – Subgrade Dynamic Liquifaction	FH - SDL -	8
			Subtotal	8
	Total Snow and Ice Scenario Hazards			11

5.4 Characterization of Identified Railway Ground Hazard Scenarios: CN Western Canada.

The subsequent chapters in this thesis characterize each of the railway ground hazard scenarios within their Level III classification grouping, according to the initiating event. The groupings include rock landslides, debris landslides, earth landslides, settlement, collapse, overland / through flow erosion, and sub-aqueous flow erosion. Characterization of snow and ice hazards is not within the scope of this Thesis.

Each chapter is structured according to the characterization system presented in Chapter 4. The general outline for each chapter is as follows:

1. Introduction, which includes a correlation of the frequency and severity of loss associated with scenarios in the group with the results of Chapter 3.
2. Description of the failure modes and effects analysis (FMEA) trees for each scenario in the group, including case examples.
3. Description of ground hazard event ground conditions and processes.
4. Description of rates, timing and lag time of the railway ground hazard scenario system failure.
5. Discussion of track stability states for scenarios in group.
6. Identification, description and suggested preparatory causal factors associated with group.
7. Identification, description and suggested trigger causal factors associated with group.
8. Suggested consequence likelihood factors for scenarios in group.

Available specific information systematically recorded on the geotechnical inspection form, pertinent to each of the above characteristics, was derived from the database and inserted in the appropriate section in the subsequent chapters. The sources of the information and methodology used to interpret and summarize this information are described in the following sections.

5.4.1 Characterization of Ground Conditions and Processes

The geotechnical inspection form provides space for notes regarding landslides, or slope movements as they are referred to on the form. However, there are limited fields on the form that specifically describe the ground conditions and processes associated with the remaining ground hazard event types. The fields that do exist for material types such as soil or rock types, surficial geology, rock/debris/earth (coarse, fine, cohesive) and difficult soil type were most often not filled in because either there was not enough time, or in many cases, vegetation cover obscured the ground surface. There is therefore limited systematic information available from the geotechnical inspection form for this information.

However, significant ground condition and process information can be either inferred, or taken directly from the name subjectively given to the ground hazard scenario. The name in essence describes the processes, a series of changes, involved in the ground hazard scenario. For landslides, Cruden and Varnes's (1996) system describes the primary material involved in the process, but stops short of making any further distinction such as between cohesive and non-cohesive soil. Under subsidence, the type of material and mode of movement is provided in the description of the Level IV hazard class in Chapter 2. For hydraulic erosion, the process or mode of movement that produces the erosion is provided in the description of the Level IV and V class in Chapter 2, however, the material types are not specifically given. For icing hazards, the primary material type is ice and the susceptible soil types are again provided in the description of the Level III hazard class in Chapter 2. Description of snow avalanche hazards is beyond the scope of the author's expertise and is excluded in this Thesis.

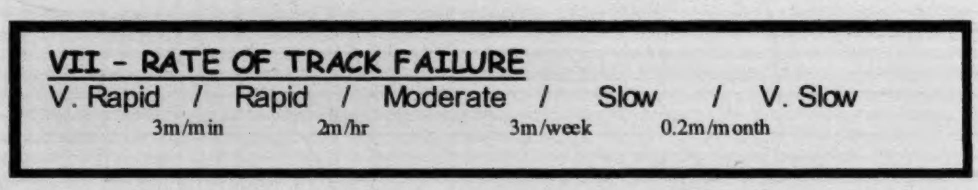
Given that the ground condition and process mode of movement is contained or can be inferred in the name given to the ground hazard, the identification and characterization of the railway ground hazard scenario in a FMEA format also provides a significant amount of this information. Therefore to cover off the characterization of ground conditions and processes, and to provide some guidance developing the list of causal factors for each group, a short description of the initiating event ground condition and processes is provided in the corresponding section in Chapters 6 through 11. These descriptions are aided by the terrain classification system used in Cruden and Thomson (1987) "Exercises in Terrain Analysis".

5.4.2 Rates and Timing of CN Western Canada Railway Ground Hazard System Failure

One of the more significant factors controlling the likelihood of track failure, service disruption and derailment, is the rate and timing as described in Chapter 4 at which ground hazard scenarios occur. More specifically, the important characteristic is the potential time period between the initiating hazard event and track failure. This requires an estimate of the rate of each hazard event, along with an estimation of the temporal aspects of the events including incremental versus continuous processes, lag time between events and the time of day or year the event is likely to occur.

Not only does the rate contribute to the force the ground hazard event exerts on the track structure, but it also determines the amount of warning time available. Box VII – Rate of Track Failure on the Geotechnical Inspection Report form shown in

Figure 5-3 was included on the form to track the subjectively assessed rate that track failure, as defined in Chapter 4, was estimated to occur. The movement rates are consistent with Cruden and Varnes (1996) for landslide rates of movement.



VII - RATE OF TRACK FAILURE

V. Rapid / Rapid / Moderate / Slow / V. Slow

3m/min 2m/hr 3m/week 0.2m/month

Figure 5-3 Box VII off the Geotechnical Inspection Report form, used to track subjectively assessed track failure.

A summary of the results is sorted by ground hazard scenario and grouped into the level III ground hazard classes provided in the corresponding sections in Chapters 6 through 11. When filling in this portion of the form, the author considered the ultimate ground hazard event that would result in track failure.

The results are generally as expected; rock landslides dominated by rock falls are dominantly very rapid, earth landslides, settlement, channelized flow erosion and icing hazards have a uniform distribution between rapid and slow, and overland / through flow erosion is dominated by rapid rates of movement. It is suggested that these results provide useful indicators for the determination of the track, service disruption and derailment vulnerability.

5.4.3 Track Stability States

It was the author's standard protocol to subjectively assess the priority and monitoring status of the particular ground hazard location by assigning an A to D rating at the completion of each inspection. The assessment was based on the following criteria and filled out in Box IX on the form.

IX – PRIORITY and MONITORING ASSESSMENT

Assessment (A,B,C,D) – time frame (required action):

A: Imminent failure, potential for derailment (within a month or further investigation)

B: Failure could cause derailment (current year or 1-2 years)

C: Failure could affect track serviceability (long term, monitor)

D: No instability, or effectively mitigated, unlikely to impact trains (no action)

Figure 5-4 Bov IX on the geotechnical Inspection form: Previous priority and monitoring criteria, track stability states.

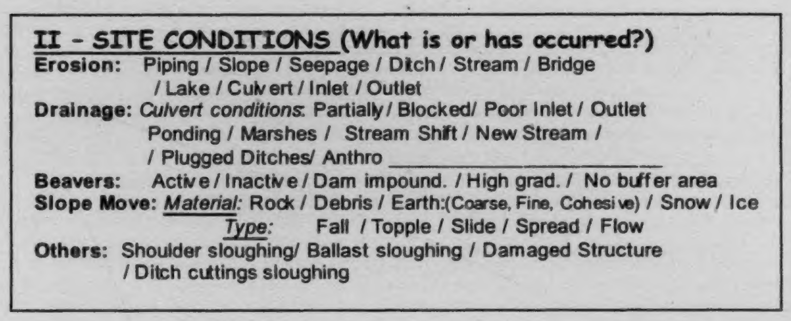
This is an essential component of the inspections as it flags the particular hazard for (A) immediate action, (B) inclusion in the planning process, (C) follow-up inspections, or (D) archiving the record. These assessments rely solely on engineering judgment. The development of a generic criterion to determine track stability states and ground hazard activity stages for railway ground hazard scenarios presented in Table 4-5 is intended to provide a more objective and repeatable means of completing this assessment using the presence or absence of preparatory and trigger causal factors. As the priority and monitoring assessments reported for each CN Western Canada railway ground hazard scenarios is subjective, and potentially contentious, it is not appropriate to report them in this thesis. Discussions on track stability states in the corresponding sections in Chapters 6 through 11 are therefore limited to qualitative discussions with no inferences drawn.

For rock landslide hazards and avulsion hazards caused by hazardous beaver activity, formal inspection protocols are set up and scheduled inspections are carried out. For other hazards, this database is used to schedule inspections and they are undertaken primarily in the spring of each year by the CN Senior Geotechnical Engineers.

5.4.4 Identify Preparatory Causal Factors and Attributes

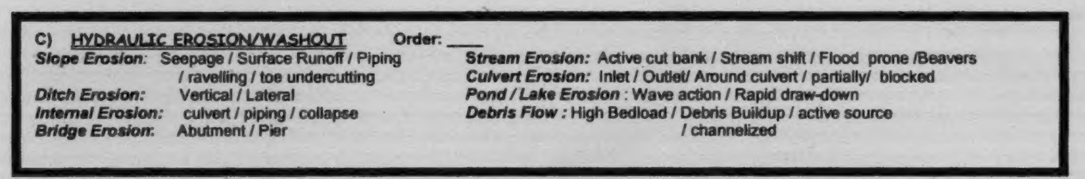
At the time the form was created, there was an appreciation for the role that trigger causal factors played in the management of railway ground hazards, but the importance of distinguishing preparatory causal factors was not yet apparent. As a result, the inspections included a systematic identification of trigger causal factors in Box V of the form, but no formal identification of the preparatory causal factors was implemented. What is included on the form is a significant amount of attribute information collected in Box II - Site Conditions (Figure 5-5), and additional fields within Box C - Hydraulic Erosion/Washout (Figure 5-6).

Most of the fields in Figure 5-7 and Figure 5-9 tend to be indicators that a preparatory causal ground condition exists, or that a process is or has been active at the site at the time of the inspection that can be attributed to be a preparatory cause of a ground hazard.



II - SITE CONDITIONS (What is or has occurred?)
Erosion: Piping / Slope / Seepage / Ditch / Stream / Bridge / Lake / Culvert / Inlet / Outlet
Drainage: *Culvert conditions*: Partially / Blocked/ Poor Inlet / Outlet
Ponding / Marshes / Stream Shift / New Stream /
/ Plugged Ditches/ Anthro ____________________
Beavers: Active / Inactive / Dam impound. / High grad. / No buffer area
Slope Move: *Material:* Rock / Debris / Earth:(Coarse, Fine, Cohesive) / Snow / Ice
Type: Fall / Topple / Slide / Spread / Flow
Others: Shoulder sloughing/ Ballast sloughing / Damaged Structure / Ditch cuttings sloughing

Figure 5-5 Box II – Site Conditions taken from the Geotechnical Inspection Report form



C) HYDRAULIC EROSION/WASHOUT Order: ____
Slope Erosion: Seepage / Surface Runoff / Piping / ravelling / toe undercutting
Ditch Erosion: Vertical / Lateral
Internal Erosion: culvert / piping / collapse
Bridge Erosion: Abutment / Pier
Stream Erosion: Active cut bank / Stream shift / Flood prone /Beavers
Culvert Erosion: Inlet / Outlet/ Around culvert / partially/ blocked
Pond / Lake Erosion : Wave action / Rapid draw-down
Debris Flow : High Bedload / Debris Buildup / active source / channelized

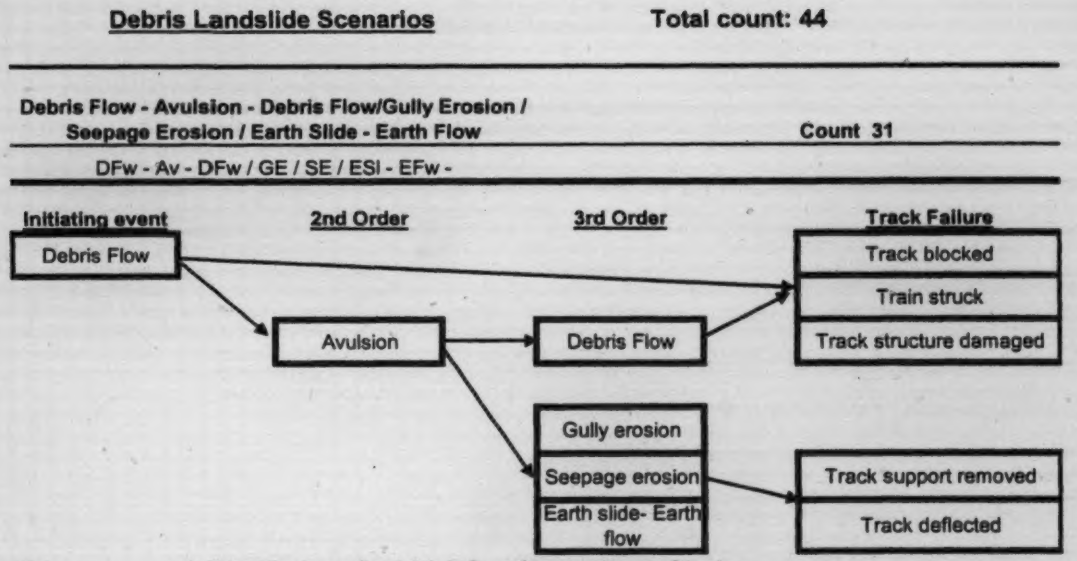
Figure 5-6 Box C) Hydraulic Erosion/Washout taken from the Geotechnical Inspection Report form

Following the form's nomenclature, the preparatory causal factors are grouped according to five categories, namely erosion, poor drainage, beaver activity, landslide material, landslide movement type and other observations. For each of the scenarios, the percentage of times each of the fields was reported was calculated and listed under these five categories. The results are presented in the appropriate sections in Chapters 6 through 11. Table 5-6 was generated to draw the correlation between these five categories and the causal factor categories developed in Chapter 4.

The discussion of preparatory causal factors, in Chapters 6 through 11, includes suggested summary listings and description of preparatory causal factors developed by the author and subdivided according to the ground conditions and the three process types namely geomorphological, physical and man or animal made. These listings are specific to the individual ground hazard event, as opposed to the entire hazard scenario. When characterizing the preparatory causal factors for the entire ground hazard scenario, it is necessary to include the preparatory causal factors for each individual hazard event. To illustrate this, consider the hazard scenario initiated by a debris flow event as shown in Figure 5-7. Aside from the preparatory causal factors for the debris flow characterization, one also has to include preparatory causal factors for avulsion of the ensuing stream and seepage, piping or earth slide susceptibility of the railway embankment. The listing and description of preparatory causal factors for the other ground hazard events are contained in their corresponding sections in Chapters 6 through 11.

Table 5-6 Correlations between the five categories on the Geotechnical Inspection Form and the causal factor categories developed in Chapter 4.

Erosion	Observation of Geomorphic Process causal factors when the erosion process is part of the evolution of a landform (I.e. natural piping, slope erosion, gullying, stream or lake erosion) or observation of Physical Process causal factors when the erosion involves natural external destabilizing forces from the natural environment around the ground hazard (I.e. Ditch, bridge, culvert or embankment erosion).
Poor Drainage	Mostly refers to inadequacies of the railway drainage infrastructure, and as such, are considered manmade process causal factors.
Beaver Activity	Observations of hazardous beaver activity are considered animal process causal factors
Landslide Material	Provides a very general identification of the Ground Conditions by identifying the landslide material type involved, according to Cruden and Varnes (1996).
Landslide Movement Type	Provides a very general identification of the Geomorphic Process causal factors involved when the landslide movement is part of the evolution of a landform or Physical Process causal factors when the landslide movement involves an embankment.
Other Observations	These observations refer to defects in the track substructure or supporting infrastructure (retaining walls) and as such are considered Manmade Process causal factors.


Debris Landslide Scenarios
Total count: 44
Debris Flow - Avulsion - Debris Flow/Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow
Count 31
DFw - Av - DFw / GE / SE / ESl - EFw -
Initiating event
2nd Order
3rd Order
Track Failure
Debris Flow
Avulsion
Debris Flow
Track blocked
Train struck
Track structure damaged
Gully erosion
Seepage erosion
Earth slide- Earth flow
Track support removed
Track deflected

Notes:
1. Primarily channelized debris flows from upstream of tracks
2. Avulsion results from debris redirecting or blocking water flow in channel, culvert or bridge
3. 3rd Order Debris flow results from new channel scour and entrainment from misdirected flow.
4. GE, SE or ESI-EFw result from misdirected water flow passing over/through the track grade

Figure 5-7 Debris flow hazard scenario example.

5.4.5 Trigger Causal Factors

The general requirement for a railway ground hazard triggering causal factor is that it initiates track failure from the railway ground hazard event, thereby changing the track from marginally stable to an actively unstable state (see Table 4-4). The summary definition for a trigger given in Section 4.5.1.2 is an external stimulus or change in preparatory causal factors that causes a near-immediate response in the form of a track failure. The list of trigger causal factor terms developed and used on the geotechnical inspection form is as follows:

IR	Intense rainfall
P	Piping
RD	Rapid Draw-down or Draw-down
TA	Train Action
PR	Prolonged Rain (significant exceptional rain)
FT	Freeze Thaw
HS	Heavy Snow
HW	High Water (high flows)
SM	Snow Melt
T	Thawing (thawing of ground frost)

- HWT High Water Table (elevated phreatic surface)
- RFL Rising Freezing Level
- A Anthropogenic

This list was expanded over time by the author, to cover most of the commonly inferred trigger causal factors associated with the railway ground hazards investigated. More technically appropriate terminology is included in brackets. It is by no means a thorough list, but it was used consistently through the past eight years of inspections.

Following the form's nomenclature, the preparatory causal factors are grouped according to five categories, namely erosion, poor drainage, beaver activity, landslide material, landslide movement type and other observations. For each of the scenarios, the percentage of times each of the fields was reported was calculated and listed under these five categories. The detailed results are presented in the corresponding section on triggers in Chapters 6 through 11.

Also included in the sections on trigger causal factors are suggested summary listings and descriptions, developed by the author, subdivided according to the three process types, namely geomorphological, physical and man or animal made. These listings are specific to the individual ground hazard event, as opposed to the entire hazard scenario. In most cases it is the trigger causal factor for the initiating event in the scenario that is also the trigger causal factor for track failure, because the chain of hazard events leading to track failure happens in relative rapid succession. This is not true is when there any kind of a time lag introduced into the scenario in which the trigger for the subsequent hazard events would become the trigger causal factor for track failure. A common example of this is channelized flow erosion triggered by high flows. The erosion acts to undermine a slope but the equalizing water pressures against the slope from the high water level act to keep the slope marginally stable. Once the water levels come down, days, months and occasionally years later, drawdown effects become the trigger causal factor for an earth slide that results in track failure. In practice the inspector might observe that some scour has occurred or suspect that it has, based on recent high flows at the base of a slope, but not observe any distress in the slope. The hazard should be upgraded to a (2) marginally stable state, with drawdown as the trigger causal factor, which can immediately or incrementally result in track failure.

Similar to preparatory causal factors the, listing and description of trigger causal factors for the other ground hazard events are contained in their corresponding sections in Chapters 6 through 11.

5.5 Summary

Chapter 5 describes the processes used to populate the database of railway ground hazards in CN Western Canada between 1997 and 2005; presents the 40 railway ground hazard scenarios identified to characterize the 2,790 ground hazard sites in the database; and describes the process used to characterize the railway ground hazard sites using the methodology developed in Chapter 4.

Coupled with the results of Chapters 2, 3, 4 and 5, this chapter completes the requirements of Section 5.3.4 Hazard Identification of the CAN/CSA-Q850-97 Standard (CSA, 1997).

Identification and characterization of the railway ground hazards in CN Western Canada was accomplished through ten years of systematic inspections undertaken by or under the direct supervision of the author. Railway ground hazards were identified through; a review of the loss records; hi rail inspections by either track inspectors or geotechnical engineers; train crew observations; 3rd party observations; helicopter inspections; incident reports; maintenance records; air photo analyses; or by inference.

The geotechnical inspections, which exclude rock slope inspections, were completed using a standard geotechnical inspection form developed by the author, generally consistent with the Chapter 4 risk characterization methodology. The resulting database represents a comprehensive source of structured railway ground hazard information used in this thesis to risk characterize CN's railway ground hazards in Western Canada. The form captures the track geometry, site conditions, general comments, the ground hazard classification and the subjectively assessed scenario, potential trigger causal factors, consequences of failure, rates of track failure and hazard ratings, if available for the ground hazard type. From this information, a priority and monitoring assessment is completed and, if warranted, a preliminary mitigation scoping is completed.

The resulting database contains approximately 1,300 of the most recent records from each non-rock fall hazard site identified. CN's rock fall hazard database, containing

1,600 rock fall hazard sites, was taken from the CN rockfall hazard and risk assessment (CNRHRA) system, bringing the total number of ground hazard sites in the database to 2,900.

Forty railway ground hazard scenarios are identified from the database covering 2,791 of the approximate 2900 ground hazards identified, using primarily the information contained in the records, but also supported by the author's familiarity with the sites. The chapter presents an initial listing of the railway ground hazard scenarios grouped by the initiating ground hazard event according to the Level II classification, namely Landslides, Subsidence, Hydraulic Erosion and Snow and Ice.

The 1,824 landslide hazard sites are further subdivided into *rock landslides* containing 1,610 hazard sites with two scenarios identified; *debris landslides* containing 44 hazard sites with four scenarios identified; and *earth landslides* containing 140 hazard sites with six scenarios identified.

The 54 subsidence hazard sites are further subdivided into *subgrade plastic deformation* containing 20 hazard sites with two scenarios identified; *consolidation* containing 17 hazard sites with three scenarios identified; *compression* containing 13 hazard sites with one scenario identified; and *subgrade dynamic liquefaction* containing 4 hazard sites with two scenarios identified.

Although no ground hazard scenarios were identified with a *collapse* hazard as an initiating event, these hazards are known to exist and are contained in other scenarios identified.

The 902 hazard sites initiated by hydraulic erosion hazard events are further subdivided into *overland/through flow erosion,* containing 151 hazard sites with six scenarios identified; *avulsion upstream of the tracks* containing 469 hazard sites, predominantly the result of hazardous beaver activity, with two scenarios identified; *channelized flow erosion parallel to the tracks* containing 257 hazard sites with six scenario identified; *channelized flow erosion at bridge crossings* containing 22 hazard sites with three scenarios identified; and *wave erosion* containing three hazard sites with one scenario identified.

Snow avalanche and icing hazard sites were not systematically identified in this database and are thus not characterized in this thesis.

The final section in Chapter 5 describes the structure utilized in the risk characterization of the identified railway ground hazards identified in CN Western Canada in Chapters 6 through 11. These chapters characterize the ground hazard scenarios grouped according to the initiating event into rock landslides, debris landslides, earth landslides, settlement, collapse, overland / through flow erosion, and sub-aqueous flow erosion. Each chapter is structured according to the characterization system presented in Chapter 4.

The introduction includes a correlation of the frequency and severity of loss associated with scenarios in the sub group, with the results of Chapter 3.

The failure modes and effects analysis (FMEA) trees for each scenario in the subgroup are presented and explained, supported in most cases with a case example.

The ground conditions and processes associated with the initiating ground hazard events within the subgroup are identified and described.

The rates, timing and lag time of the railway ground hazard scenario system failure assessed from the database, or inferred from case examples, are presented and discussed.

The track stability states for the scenarios in the subgroup are discussed using the results of the priority and monitoring assessments completed on the geotechnical inspection forms. A correlation is discussed between the subjective assessments and the new methodologies developed in Chapter 4 to assess the ground hazard activity stage and, by inference, the track stability stage using the presence or absence of preparatory or trigger causal factors.

The preparatory causal factors associated with the subgroup are identified, described and suggested, using information derived from the database under the categories of erosion, poor drainage, beaver activity, landslide material, landslide movement type and other observations. Also included, are suggested summary listings and description of preparatory causal factors developed by the author, subdivided according to the ground conditions and the three process types, namely geomorphological, physical and man or animal made.

The trigger causal factors associated with the subgroup are identified, described and suggested using information derived from the database. Also included are suggested summary listings and description of trigger causal factors developed by the author subdivided according to the three process types namely geomorphological, physical and man or animal made.

The consequence likelihood factors for track failure, derailment and derailment consequences are suggested for the scenarios in the subgroup.

Chapter 6 Characterization of Railway Rock Landslide Hazard Scenarios: CN Western Canada

6.1 Introduction

From the review of loss records presented in Chapter 3, between 1992 and 2002, train accidents attributable to rock landslides, predominantly rock falls, occurred at an average frequency of 2.4 per year, with a severity of $63,000 direct costs per accident accounting for $150,000 per annum. The large majority of these incidents occurred on the CN Edmonton to Vancouver corridor. This chapter steps through the characterization of the identified rock landslide hazard scenarios from the CN Western Canada ground hazard database that would have been attributed to these loss records. Following an illustration and description of the hazard scenarios initiating with rock landslides, the chapter characterizes rock landslide ground conditions and processes, rates and timing of system failure and track stability states. This is followed by identification and characterization of rock landslide hazard scenario trigger and preparatory causal factors, either observed or interpreted by the author, followed with an identification of rock landslide controlling attributes. The chapter closes with a summary of rock landslide hazard scenarios consequence likelihood factors for track failure, service disruption and derailment.

6.2 Rock Landslide Hazard Scenarios FMEA.

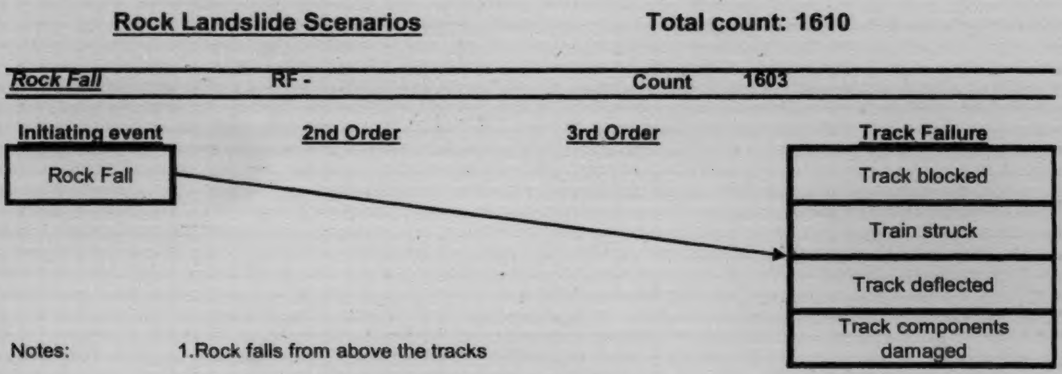
The short list of identified hazard scenarios initiating with rock landslide events is presented in Table 6-1. The vast majority, 99.5%, are classified as simple rock fall scenarios and the remaining 0.5% are classified as simple rock slide scenarios. Following is an illustration and description of the FMEA for each of these.

Table 6-1 Summary of rock landslide hazard scenarios CN Western Canada

Level III Subgroups	Ground Hazard Scenario	Coding	Count
Rock Landslides	Rock Landslides		
	Rock Fall	RF -	1603
	Rock Slide	RSI -	7
	Subtotal		1610

6.2.1 *Rock fall Hazard Scenario*

Figure 6-1 depicts a simplified FMEA for the rock fall hazard scenario. This scenario initiates with detachment of a rock mass from its intact rock source, involving one or many particles. The particles then fall, bounce or roll to the tracks and cause track failure by blocking the track, striking a train or equipment, deflecting the track, or damaging the track components. It is likely that a significant number of these scenarios actually have rock slides or rock topples as the initiating event, however it is not possible to determine this from the existing records.


Rock Landslide Scenarios
Total count: 1610
Rock Fall
RF -
Count
1603
Initiating event
2nd Order
3rd Order
Track Failure
Rock Fall
Track blocked
Train struck
Track deflected
Track components damaged

Notes: 1.Rock falls from above the tracks

2. May be preceded by a rock topple or rock slide

Figure 6-1 Simplified FMEA for the rock fall hazard scenario

6.2.2 *Rock slide Hazard Scenario*

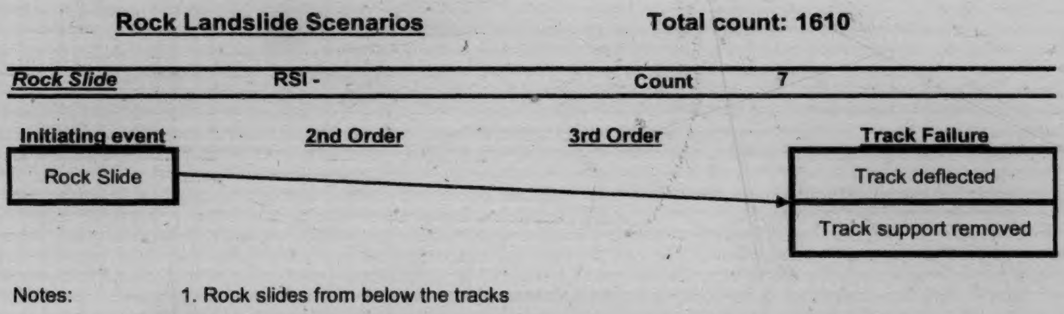

Rock Landslide Scenarios
Total count: 1610
Rock Slide
RSI -
Count
7
Initiating event
2nd Order
3rd Order
Track Failure
Rock Slide
Track deflected
Track support removed
Notes:
1. Rock slides from below the tracks

Figure 6-2 depicts a simplified FMEA for the rock slide hazard scenario. A review of the records indicate that this scenario initiates with a rock slide from under the tracks which causes track failure by either deflecting the track surface or by removing support from the track structure.

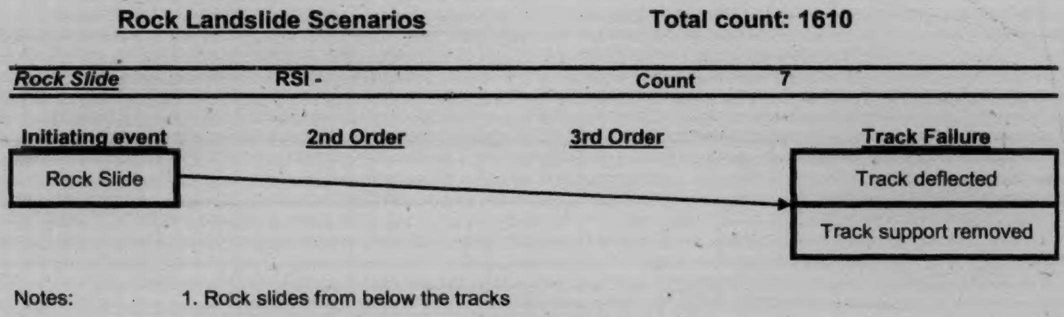

Rock Landslide Scenarios
Total count: 1610
Rock Slide
RSI -
Count
7
Initiating event
2nd Order
3rd Order
Track Failure
Rock Slide
Track deflected
Track support removed
Notes:
1. Rock slides from below the tracks

Figure 6-2 Simplified FMEA for the rock slide hazard scenario

6.3 Rock Landslide Hazard Events Ground Conditions and Processes

In this section the ground conditions and processes associated with rock landslide events is discussed. Rock landslides are characteristically of three types, namely falls, topples or slides and are controlled primarily by the discontinuities in the rock mass.

6.3.1 Rock falls

A rock fall occurs when a rock mass is detached from a steep slope or cliff along a surface on which little or no shear displacement takes place, and descends by free fall, bouncing or rolling. From field tests, Ritchie (1963) produced a ditch design chart that indicated that *free fall* (i.e. rocks that tend to stay close to the face and land near the toe of the slope) generally occurs when the slope below the rock mass exceeds an angle of 76°, *bouncing* and *spinning* occurs on slopes at less than this angle and *rolling* occurs on slopes with angles less than 45°. A rock fall event may involve the displacement of a single fragment or many. It commonly begins by detachment of a more or less coherent block that fragments along its trajectory.

6.3.2 Rock Topples

A rock topple occurs when a rock mass rotates about a point or axis located below the centre of gravity of the displaced mass. Topples can occur when the dominant, pervasive, joint pattern strikes sub-parallel to the slope direction and dips steeply into the slope. A rock landslide of this type is classed as a rock topple hazard if the event can directly affect or cause track failure. According to Cruden and Varnes (1996), toppling can be driven by gravity exerted from material, above the displaced material or from water or ice in cracks in the mass. The more common modes of toppling are described below:

Block toppling - occurring where individual columns are divided by widely spaced joints. The short columns forming the toe of the slope are pushed forward by forces from longer overturning columns behind them. This sliding at the toe allows further toppling to develop higher up the slope.

Flexural toppling - occurring in rocks of one preferred discontinuity system. Continuous columns of rock, separated by steeply dipping discontinuities, break in flexure as they bend forward. Sliding, excavation or erosion at the toe allows the toppling process to start, It then regresses back into the rockmass, forming deep, wide tension cracks.

Chevron toppling - Block topples where the dip of the toppled blocks is constant and the change of dip is concentrated at the surface of rupture.

Block-flexure topples - The toppling columns in this case result from accumulated displacements on the cross joints. Due to the large number of small displacements in this type of toppling, there are fewer tension cracks than in flexural toppling and fewer edge to face contacts and voids than in block toppling.

Other Toppling Modes - All other modes of toppling involve a primary failure mode of sliding or physical breakdown of the rock and toppling is induced as a result of this primary failure

As toppling processes are characteristically slow with small incremental movements they are more apt to be an initiating hazard event preceding a rock fall or rock slide.

6.3.3 Rock Slides

A rock slide occurs when a rock mass undergoes shear strain or displacement across adversely oriented discontinuities or weak layers. Rock slides are most often controlled by discontinuities in the rock mass such as faults, joints, bedding surfaces or the contact between rock and residual or transported soils. Common types of movement include:

Planar – occurs when a discontinuity daylights in the rock slope or fails at the toe due to buckling, simple bilinear slab failure or ploughing. Modes include single or multiple blocks with single or multiple planar failure surfaces.

Wedge – occur when the intersection of two discontinuities strikes obliquely to the slope face and the line of intersection dips out of the slope and daylights in the slope face.

Rotational – occurs in rock masses that are either highly fractured or composed of material with low intact strength.

From above the tracks, rock slides are commonly the initiating hazard event preceding a rock fall or a dry debris flow. All of the rock slide hazards identified in the database are down slope or directly under the track. A *rock topple-rock slide* can occur when the surface of rupture in a topple aligns to form a continuous planar or stepped rupture surface that facilitates sliding.

6.4 Rock Landslide Hazard Scenarios Rates and Timing of Track Failure

Table 6-2 presents a summary of the subjectively estimated rates of track failure for the CN Western Canada rock landslide hazard scenarios. As expected the rates are very rapid to extremely rapid, and may or may not be preceded by minor movements. Rock Slides range from slow to very rapid.

Table 6-2 Rates of tracks failure from rock landslide hazard scenarios

				Percentage of Ground Hazards Reporting this Speed				
Level III Subgroups	**Ground Hazard Scenario**	**Coding**	Count	Very Rapid	Rapid	Moderate	Slow	Very Slow
Rock Landslides	**Rock Landslides**							
	Rock Fall	RF -	1603	97%	0%	0%	0%	0%
	Rock Slide	RSI -	7	14%	0%	14%	14%	0%
		Subtotal	**1610**	**97%**	**0%**	**0%**	**0%**	**0%**

Timing of rock falls depends, as expected, on the trigger causal factors, specifically freeze and thaw cycles, but also coincident with intense rain or heavy snow melt. For instance as presented in Section 6.7.1, the highest frequency of rock falls on the CN Kamloops to Vancouver corridor is early in the year, when the mean daily temperatures climbs above 0°C, indicating the onset of daily freeze-thaw cycles. On the CN Squamish Subdivision between Vancouver and Squamish, B.C., there is an increased frequency of rock falls in May and June of the year, which corresponds to a rapid tree root growth period which is a significant trigger causal factor for rock falls in this region.

6.5 Rock Landslide Hazard Scenarios Track Stability States.

Rock landslides tend to occur suddenly, generally with little pre-warning of an event. They are also difficult to monitor effectively due to their remoteness from the track and the shear size and number of them. At the same time, preparatory process causal factors are constantly at work, and as a result rock fall hazards tend to remain in a **(3)** track stability state requiring periodic monitoring in the form of inspections. The timing and level of effort for these inspections at CN are established based on the CN RHRA (Pritchard et al, 2005) quantitative risk assessment system.

6.6 Rock Landslide Hazard Scenarios Preparatory Causal Factors

6.6.1 Observed Rock Landslides Preparatory Causal Factors

Error! Reference source not found. presents the preparatory causal factors identified for each rock landslide hazard scenario according to the categories of erosion, poor drainage, beaver activity, landslide material, landslide movement type and other observations. The percentage of each preparatory causal factor is presented in brackets.

As the inventory of rock fall hazards came from the CN Rockfall Hazard and Risk Assessment (RHRA) system, specific preparatory causal information is not available in the database. For rock slides scenarios, piping erosion, seepage erosion, slope wash erosion, and shoulder sloughing were identified as preparatory causal factors.

Preparatory Causal Factors: CN Western Canada Railway Ground Hazard Scenarios

[illegible]	[illegible]	[illegible]	Erosion	Poor Drainage	Beaver Activity	Landslide Material	Landslide Movement Type	Other Observations
Rock Landslides	**Rock Landslides**							
	Rock Fall	1603				Rock (100%).	Fall (100%).	
	Rock Slide	7	Piping (14%),Slope (29%),Seepage (29%).			Rock (100%),Earth (29%),Earth Cohesive (14%).	Fall (29%),Slide (86%).	Shoulder Sloughing (29%),Ballast Sloughing (14%).
	Subtotal	1610	Slope (0%),Seepage (0%),Ditch (0%),Stream (0%).			Rock (100%),Debris (0%),Earth (0%),Earth Cohesive (0%).	Fall (100%),Topple (0%),Slide (1%),Flow (0%).	Ballast Sloughing (0%).

Table 6-3 Preparatory causal factors identified for each rock landslide hazard scenario grouped into erosion, poor drainage, beaver activity, landslide material, landslide movement type and other observations. The percentage each preparatory causal factor was reported for each hazard scenario is presented in brackets.

6.6.2 Suggested Rock Landslides Preparatory Causal Factors

There are several causes for the rock landslides on Canadian railways particularly through the Western Cordillera. Due to intense folding and faulting, rock masses along the lines are generally broken, sometimes to the point that they lack cohesion (Peckover, 1972). In Canada, Quaternary glaciations and postglacial down cutting of river systems has resulted in over-steepening of natural rock slopes. As well, rock landslides are inherently more common along railways in high relief terrain due to gradient and curvature restrictions. These result in rock cuts, which in effect, impose an additional artificial over-steepening of already over steepened rock slopes. Heavy blasting used during the original construction of the railway has intensified the damage. Worsening the situation is the incrementally higher extremes in both temperature and precipitation experienced in Canada.

In Table 6-4 the author provides a suggested glossary of the preparatory causal factors for rock landslides expanded from Cruden and Varnes (1996) and the Working Party on World Landslide Inventory (WP/WLI) (Popescu, 1994) including causal factors and responses from the CNRHRA system (Pritchard, 2005).

Table 6-4 Preparatory factors for railway rock landslide hazards

Preparatory Causal Factors – rock landslides		Description
1.Ground Conditions		
WkM	Weak materials	Degradable materials from igneous, metamorphic and particularly sedimentary rocks cause the rock mass to be weak and this has a significant influence on the stability of a rock slope.(Piteau and Peckover, 1978)
WdM	Weathered materials	Reduced strength of rock mass at surface or along beds or surfaces due to chemical weathering decomposing the rock to clay minerals.
SM	Sheared materials	Reduced shear strength of rock mass and ability for water to enter makes it susceptible to high water pressures and frost wedging
JFM	Jointed or fissured materials	Reduced shear strength of rock mass and ability for water to enter and susceptible to high water pressures and frost wedging.

Preparatory Causal Factors – rock landslides		Description
AOMD	Adversely oriented mass discontinuity	Bedding, schistosity, etc adversely oriented predisposes rock mass to rock landslides.
AOSD	Adversely oriented structural discontinuity	Pervasive fault, unconformity, contact, etc adversely oriented, predisposes rock slope to rock landslides.
CP	Contrast in permeability	Permeability contrast causes build up of water pressures resulting in reduced effective stress. Thrust forces and preferred flow paths cause increased and concentrated seepage from the face. Promotes ice wedging.
CS	Contrast in stiffness	Stiff, dense material over plastic materials exposed on rock slope causes time dependent loosening of upper stiff material resulting in rock landslides.
LSV	Large source volumes	Rock landslide hazard increased when the volume of the rock mass that can detach increases.
AFS	Adverse fragment sizes	Particle sizes between 0.3 and 1m in diameter have higher derailment potential raising the hazard level.
SS	Steep slope	Over steep rock slopes have reduced lateral and vertical support and result in higher impact rock falls.
LS	Long slope	Longer slopes are more likely to generate rock landslides involving larger volumes.
CS	Channelized slopes	Channels concentrates rock falls run-out paths causing concentrated debris distribution.
AB	Absence of barriers	Absence of natural or anthropogenic barriers or catchment area increases the likelihood of rock reaching the track.
2.Geomorphological Processes		
TVU	Tectonic or volcanic uplift	Introduces discontinuities into the rock mass and may expose or over steepen the rock slope.
FET	Fluvial erosion of slope toe	Ongoing and periodic stream erosion of rock slopes below tracks destabilizes slope by changing the geometrey or undermining a rotational, planer or wedge failure(see Figure 6-3)

Preparatory Causal Factors – rock landslides		Description
WET	Wave erosion of slope toe	Ongoing and periodic wave erosion of rock slopes below tracks destabilizes slope by changing the geometrey or undermining a rotational, planer or wedge failure.
SE	Subterranean erosion	Material can be removed from below by solution or piping effectively loosening the rock mass and may cause a rock landslide hazard.
VR	Vegetation removal	Removal by natural means such as forest fire, drought or wind can increase water infiltration, remove the stitching effect of roots and decreases evapotranspiration.
3.Physical Processes		
LLISM	Low level Intense snow melt	Causes an abundance of free water to infill cracks causing water pressure build up.
SAR	Significant antecedent rainfall	Causes an abundance of free water to infill cracks causing water pressure build up.
EQ	Earthquake	May play a role as a preparatory cause by loosening the rock mass incrementally.
VE	Volcanic eruption	Siesmic activity associated with a volcanic eruption may play a role as a preparatory cause by loosening the rock mass incrementally.
T	Thawing	Thawing of a rock mass results in a negative temperature gradient into the rock and can set up the conditions for frost wedging.
FW	Frost wedging	Also known as ice jacking, caused by the expansion of water turning to ice during freeze-thaw cycles. As a preparatory cause it serves to open cracks and increase likelihood of a rock landslide. Affect is enhanced when there is a negative temperature gradient into the rock whereby the unfrozen free water at the surface encounters rock at temperatures less than -3°C. This occurs predominantly in late winter.
FT	Freeze-and-thaw weathering	Rocks may disintegrate losing shear strength under cycles of freezing and thawing or thermal expansion and contraction. (Cruden and Varnes, 1996)

Preparatory Causal Factors – rock landslides		Description
SS	Shrink and swell weathering	Dry weather may cause desiccation cracking of weak or weathered rock along pre-existing discontinuities, such as bedding planes.(Cruden and Varnes, 1996)
CW	Chemical weathering	Reduced strength of rock mass at surface or along beds or surfaces due to chemical weathering decomposing the degradable materials within the rock to weaker materials such as clay minerals.
V	Vegetation	Often a rock fall is brought to failure by roots prying open cracks.
WPD	Water pressure in discontinuities	Causes a build up of water pressures in the rock mass resulting in reduced effective stress. Thrust forces bring the rock slope closer to failure in the form of a rock landslide.
4.Man-made or animal processes		
ET	Excavation of rock slope at its toe	Excavation of a rock slope at the toe can result in day lighting adversely oriented discontinuities creating a rock landslide hazard.
OS	Over steepening	Cut slopes impose an additional artificial over-steepening of already over-steepened natural rock slopes.
EB	Excessive blasting	Heavy blasting used during original construction of the railway intensifying the damage to the rock mass.
LSC	Loading of slope on its crest	Waste dumps, embankments or structural weight increases the loading on the rock slope increasing the destabilizing forces and brings the slope closer to failure.
IM	Ineffective mitigation	Absence or ineffective mitigation on a rock slope increases the likelihood of a rock landslide.
VR	Vegetation removal	Deforestation or vegetation denudation of upper slopes and rock slopes increases infiltration of water into the groundwater, reduces evapotranspiration and suction provided by the trees and plants.

Preparatory Causal Factors – rock landslides		Description
Ir	Irrigation	Increases groundwater recharge to the rock mass resulting in reduced effective stress. Thrust forces bring the rock slope closer to failure in the form of a rock landslide.
WLU	Water leakage from utilities	Increases groundwater recharge to the rock mass resulting in reduced effective stress. Thrust forces bring the rock slope closer to failure in the form of a rock landslide.
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can increase groundwater recharge to the rock mass resulting in reduced effective stress. Thrust forces bring the rock slope closer to failure in the form of a rock landslide.

Figure 6-3 provides a case example of an observed bank erosion of a rock slope, a hazard and a preparatory causal factor that increased the likelihood of track failure resulting from a rock landslide from beneath the track structure.

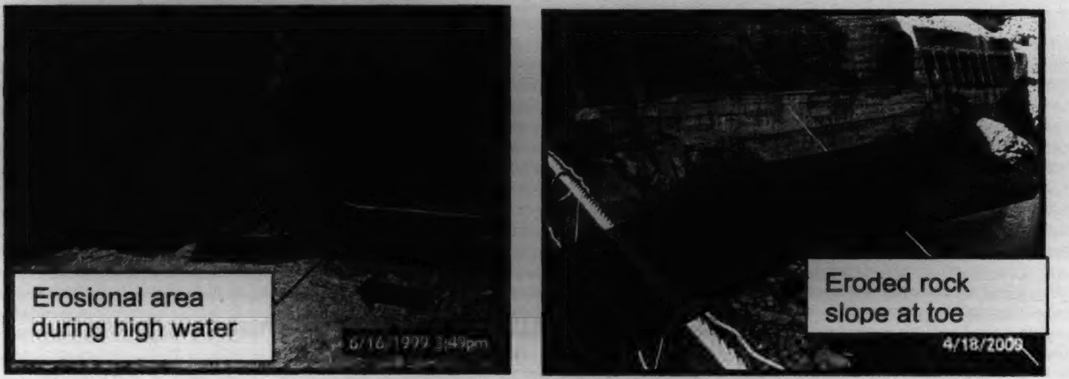


Figure 6-3 Fluvial erosion of a rock slope, FET, below the track at Skoonka, Mile 80.4 CN Ashcroft Subdivision. (Photos taken by Tim Keegan, ref. CN File 4670-ASH-80.4)

6.7 Rock Landslide Hazard Scenarios Trigger Causal Factors

6.7.1 Observed Rock Landslide Scenario Trigger Causal Factors

Figure 6-4 is a plot modified from Peckover (1972) of rock landslide event records compared to mean monthly temperature and precipitation on the CN Yale Subdivision along the Fraser River valley between Boston Bar and Chilliwak B.C. from 1933 to 1970. A similar plot compiled by the author from rockfall reports on the CN Yale Subdivision for 1995 to 2003 is presented in Figure 6-5. The plots show a significant correlation between rock landslide events and the mean daily temperature climbing above 0°C. This suggests that the most significant trigger causes for rock landslides include snow melt, freeze and thaw, and frost wedging (ice jacking). They also suggest that antecedent precipitation, both snow and rain, in November through January represents a significant preparatory cause of the spike in rock landslides in February. This useful example of the distinction between a preparatory and trigger cause suggests the trigger to monitor is the mean daily temperature. A record of heavy antecedent precipitation might lead to more intensive monitoring.

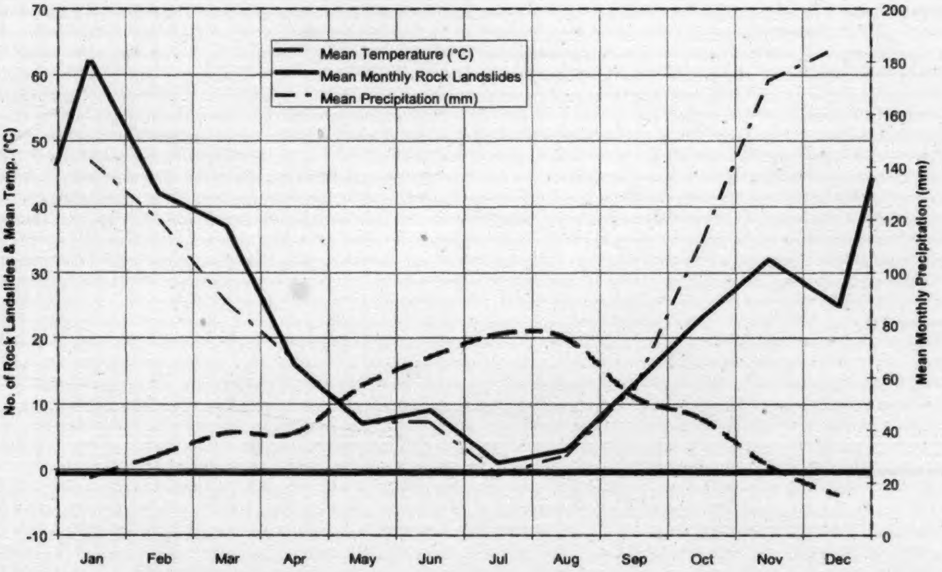


Figure 6-4 No. of rock landslide events versus temperature and precipitation along CN's Yale Subdivision – 1933 to 1970

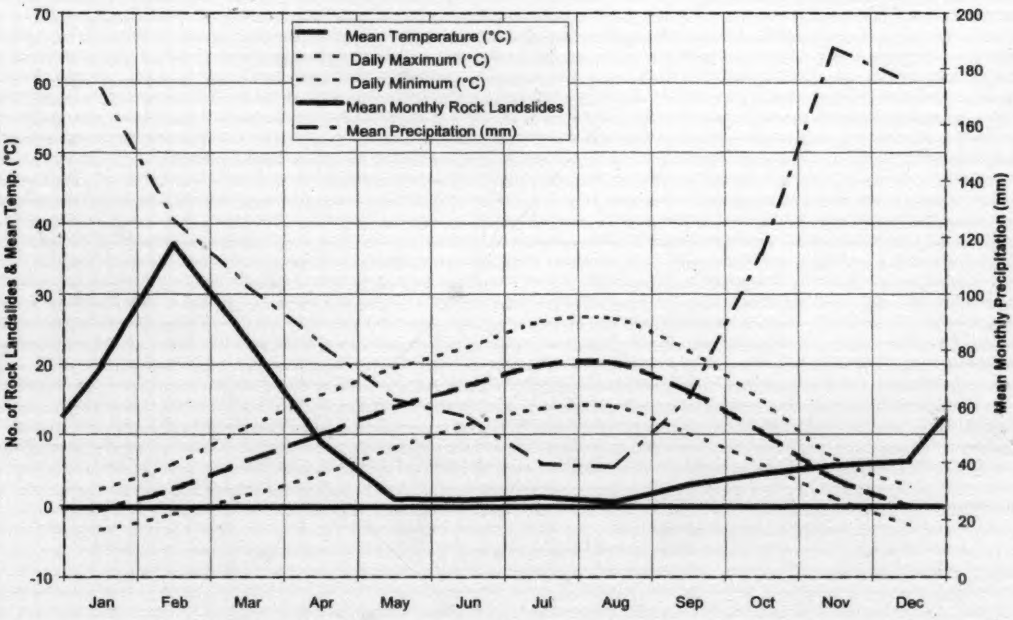


Figure 6-5 Number of rock landslide events versus temperature and precipitation along CN's Yale Subdivision – 1995 to 2003 (CN rockfall occurrence data base, climatic data from Environment Canada)

Error! Reference source not found. presents the trigger causal factors recorded for each rock landslide hazard scenario from the database. The predominant trigger causal factors in all categories include intense rain, prolonged or significant antecedent rain (SAR), daily freeze-thaw cycles, snow melt, raising freezing level, and thaw. The common denominator in most of these factors is the introduction of free water into the rock discontinuities which results either in a build up of water pressure in the discontinuity, flow erosion, or ice jacking as the free water refreezes.

Trigger Causal Factors: CN Western Canada Railway Ground Hazard Scenarios

Level III Subgroups	Ground Hazard Scenario	Count	Intense Rain	Prolonged Rain	High Water	High Water Table	Piping	Freeze/Thaw	Snow Melt	Raising Freezing Level	Rapid Drawdown	Heavy Snow	Thaw	Anthropogenic	Train Action
Rock Landslides	**Rock Landslides**														
	Rock Fall	1803	98%	98%	0%	0%	0%	99%	98%	97%	0%	0%	97%	0%	0
	Rock Slide	7	57%	71%	0%	43%	0%	14%	43%	0%	0%	0%	29%	0%	14
	Subtotal	**1810**	**98%**	**97%**	**0%**	**0%**	**0%**	**98%**	**97%**	**97%**	**0%**	**0%**	**97%**	**0%**	**0**

Table 6-5 Trigger causal factors identified for each rock landslide hazard scenario identified. The percentage each trigger causal factor was reported for each hazard scenario and each hazard scenario grouping is presented.

6.7.2 Rock Fall Trigger Causal Factors: CN Yale Mile 5.3 Case Example

A notable example of essentially all of these trigger causal factors is the rockslide-rock fall that occurred at Mile 5.3 of the CN Yale Subdivision on the early morning of December 23, 2005 illustrated in Figure 6-6.

The estimated 3,000 m^3 rockslide-rock fall event which closed the CN mainline for five days was preceded by two weeks of freezing temperatures with the average daily temperature estimated at -5°C and a snow cover of 25 cm to 50 cm at the level of the rockslide. The day before the event, a weather system moved in, raising the mean daily temperatures to approximately +5°C introducing an intense snow melt trigger causal factor. As well, the weather system brought 12 to 24 hours of moderate to intense rain, introducing both intense rain and significant antecedent rain. The rain on snow combination is considered a separate trigger causal factor because the latent heat in the rain water accelerates the snow melt when compared to the normal response to 0°C air temperatures. The combined triggers of snow melt, precipitation and rain on snow provided an abundance of free water which apparently entered the previously dilated rock mass, a preparatory causal factor, resulting in a reduction in effective stresses and introduction of thrust forces. The other trigger causal factor that likely contributed was the freeze-thaw condition which would have resulted in ice jacking caused by free water entering the rock mass that subsequently froze either due to night time freezing air temperatures or due to freezing temperatures of the rock mass.

The author has observed two nearly simultaneous rock falls from the source area and there was wide spread disturbance of the rock mass indicated by recent dilations and numerous subsequent rock falls in the weeks that followed. These observations underscore the significant effect that a combination of several trigger causal factors can have on the state of a given ground hazard, not only bringing the hazard to the (1) actively unstable state, but also bringing significant other portions of the ground hazard to the (2) marginally stable state. Also of note was that this was the only incident of its kind in the surrounding area which includes the Fraser Canyon from Boston Bar, BC to Hope, BC. It is the author's conjecture that this site was the only location where this particular combination of relevent preparatory and trigger causal factors occurred simultaneously. It is also suggested that the elevation of the source location played a role in creating a unique combination of freezing level and rain or snow.

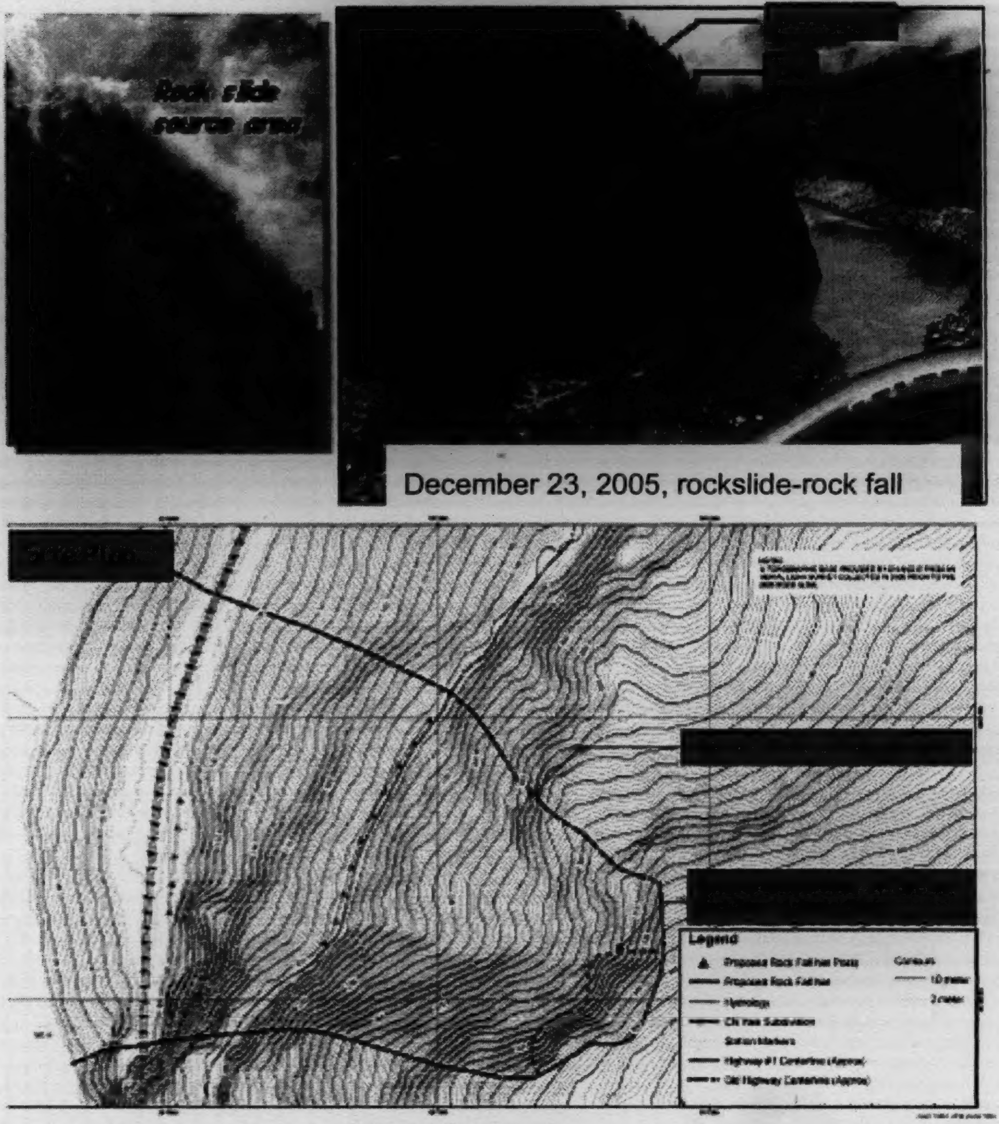

Rock slide source area
December 23, 2005, rockslide-rock fall
Site Plan
Legend
Proposed Rock Fall Net Posts
Proposed Rock Fall Net
Hydrology
CN Yale Subdivision
Station Markers
Highway #1 Centerline (Approx)
Old Highway Centerline (Approx)
Contours
10 meter
2 meter

Figure 6-6 Photos and site plan illustrating rock slide-rockfall case example. Original event occurred 4:00AM on December 23, 2005 at Mile 5.35 of CN Yale Subdivision. (photos from Tim Keegan, CN file 4670-YLE-5.35)

6.7.3 Suggested Rock Landslide Scenario Trigger Causal Factors

In

Table 6-6 the author suggests a glossary of trigger causal factors for rock landslides.

Table 6-6 Trigger causal factors for railway rock landslide

Trigger Causal Factors – rock landslides		**Description**
1.Geomorphological processes		
FET	Fluvial erosion of slope toe	Ongoing and periodic stream erosion of rock slopes below tracks reducing the stability be changing the geometry (see Figure 6-3).
WET	Wave erosion of slope toe	Ongoing and periodic wave erosion of rock slopes below tracks reducing the stability be changing the geometry.
SE	Subterranean erosion	Material can be removed from below, by solution or piping effectively loosening the rock mass and may cause a rock landslide event.
2.Physical processes		
LLISM	Low level Intense snow melt	Causes an abundance of free water to erode and under mine the rock slope, infill cracks causing water pressure build up, reduction in effective stress and potentially frost wedging.
IR	Intense rainfall	Causes an abundance of free water to erode and under mine the rock slope and infill cracks causing water pressure build up and reduction in effective stress, triggering a rock landslide.
SAR	Significant antecedent rainfall	Causes an abundance of free water to infill cracks causing sustained water pressure build up.
SE	Seepage erosion	Erosion due to seepage from a rock slope can undermine the slope and trigger a rock landslide.
EQ	Earthquake	Cyclic loading can trigger a rock landslide event when a rock landslide hazard exists.
VE	Volcanic eruption	Siesmic activity associated with a volcanic eruption may play a role as a preparatory cause by loosening the rock mass incrementally.
T	Thawing	Thawing of a rock mass results in a negative temperature gradient into the rock and can set up the conditions for frost wedging.
F	Freezing	Onset of ambient freezing temperatures can cause

Trigger Causal Factors – rock landslides		**Description**
		frost wedging to occur.
FW	Frost wedging	Also known as ice jacking, is caused by the expansion of water turning to ice during freeze-thaw cycles. As a trigger cause it serves to open cracks triggering the rock landslide. Effect is enhanced when there is a negative temperature gradient into the rock whereby the unfrozen free water at the surface encounters rock at temperatures less than -3°C. This occurs predominantly in late winter due to the availability of free water from snow melt (see Figure 6-5) but can occur at other times when water is available I.e. irrigation, groundwater springs etc.
FT	Freeze and thaw	Rocks may disintegrate losing shear strength under cycles of freezing and thawing or thermal expansion and contraction. (Cruden and Varnes, 1996). This can trigger a rock landslide.
HSF	Heavy snow fall	The weight of heavy accumulation of snow on a rock mass or on trees rooted in a rock mass can trigger a rock fall.
V	Vegetation	Rock fall is brought to failure by roots prying open cracks
WT	Wind Throw	Rock fall is brought to failure by tree roots leveraging open cracks during high winds.
WPD	Water pressure in discontinuities	Causes a build up of water pressures in the rock mass, resulting in reduced effective stress and thrust forces, triggering a rock landslide.
3.Man-made or animal processes		
ET	Excavation of rock slope at its toe	Excavation or blasting of a rock slope at the toe can result in daylighting adversely oriented discontinuities, triggering a rock landslide event
LSC	Loading of slope on its crest	Waste dumps, embankments or structural weight increases the loading on the rock slope increasing the destabilizing forces and can trigger failure.
Ir	Irrigation	Rapidly Increases groundwater recharge to the rock mass resulting in reduced effective stress. Thrust forces bring the rock slope closer to failure in the form of a rock landslide.

Trigger Causal Factors – rock landslides		Description
WLU	Water leakage from utilities	Rapidly Increases groundwater recharge to the rock mass resulting in reduced effective stress. Thrust forces bring the rock slope closer to failure in the form of a rock landslide.
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can increase groundwater recharge to the rock mass resulting in reduced effective stress. Thrust forces bring the rock slope closer to failure in the form of a rock landslide.

6.8 Rock Landslide-Hazard Scenarios: Controlling Attributes

The relevant controlling attributes for rock fall hazard scenarios include those that provide an indication of the likelihood that rocks will detach and reach the track. This is determined by the geology, geomorphology, mitigation effectiveness, slope geometry, run-out distance and presence of barriers.

Generally the controlling laws for rock falls are the physical laws of gravity, inertia, andrebound. The ability to predict rock fall behavior has until recently been limited to the use of empirical studies such as Ritchie (1963) who developed empirical ditch design charts from field tests. Since the 1980's the ability to predict rock fall behaviour has been enhanced with the development of dynamic rock fall computer programs.

Additional controlling parameters required for natural rock slope source areas situated well above the tracks include main run-out path location and run-out distance, energy and spatial distribution at track level and fragmentation of the source rock.

The main controlling attributes for rock topple or rock slide scenarios include the relative position of the rock slope and the likelihood that the rock slide or topple will occur and affect the track. This is determined by the geology, geomorphology, river morphology, effectiveness of mitigation, and slope geometry.

Both 2-dimensional and 3-dimensional dynamic rock fall computer programs are applicable to the modeling of these attributes.

6.9 Attributes for Rock Landslide Scenarios

The rock landslide landforms occur as either natural or anthropogenic steep rock slopes or cliffs as either outcrops or covered by a thin mantle (less than 10 cm thick) of unconsolidated materials and can be recognized by the exposed traces of discontinuities in the rock mass (Cruden and Thomson, 1987).

The rock type as well as the fabric of discontinuities has a profound influence on the behaviour of a rock mass. Care should be taken to determine these characteristics from the landform. Association with a debris cone at the base of a steep rock slope or fresh surfaces on the rock slope can usually identify active rock slopes. Dilatency in the rock mass, loose rocks, overhangs, adversely oriented discontinuities, pervasive discontinuities, toppling, seepage, icing and tree growth are also revealing factors of a rock landslide hazard.

6.10 Rock Landslide Hazard Scenarios Consequence Likelihood Factors

6.10.1 Track Vulnerability

Rock falls have a higher likelihood of causing track failure than other rock landslides due to their higher frequency of occurrence, mobility and speed.

A rock landslide event can result in a track failure if it removes support from the track structure; blocks or impedes the track; strikes a train; deflects the track rail surface, changes the track gauge, strikes a track structure such as a bridge or tunnel, or damages the track components. As rock landslide movements are predominantly very to extremely rapid, the events tend to occur suddenly with little to no warning.

Railways are most vulnerable to rock falls due to potential for derailment of trains by rocks falling and blocking tracks. Consistent with Abbott et al (1998a), the derailment hazard from a rock fall blocking the track increases with:

- Dimensions and shape of the largest particles reaching track level;
- Lack of lateral deflection space,
- Concentration of the debris pile,

- Wedge or slab shaped particles, and
- . Energy of impact.

Although relatively infrequent, rock falls can also cause track failure and derailments by damaging the track components, causing deflection of the track or by striking a moving train, and thus should be considered during characterization.

Rock topples and rock slides cause track failure if their displaced materials encroach on the train clearance envelope or their movements are below the tracks deflecting the track or removing support from the track structure. The main factors controlling potential track failure from a rock slide or rock topple include the relative position of the rock slope and the likelihood the rock slide or topple will occur and affect the track determined by the geology, geomorphology, river morphology, effectiveness of mitigation and slope geometry. Table 6-7 lists suggested track vulnerability factors in the vicinity of the track corresponding to the mode of track failure and the type of rock landslide. A case example of where a rockslide hazard threatened to fail the track from beneath is given in Figure 6-7.

Table 6-7 Listing of the track failure attributes corresponding to the modes of track failure and causative rock landslide hazards.

Modes of Track Failure	**Causative Ground Hazards**	**Track Vulnerability Factors**
Removing support from the track structure;	• Rock slides, topples	• Presence of retaining structures or bridges • Size, gradation and compaction of subgrade material. • Shoulder width • Ballast, sub ballast quality • Presence of revetment • Track drainage
Blocking the track;	• Rock falls, slides	• Ability to retain material (barrier walls, catch fences, ditch catchment, deflection berms) • Ability for material to pass over or under tracks (bridges, culverts, flumes, sheds) • Ditch catchment • Particle size, volume and distribution of material blocking track
Striking a train;	• Rock falls, slides	• Ability to retain material (barrier walls, catch fences, ditch catchment, deflection berm) • Ability for material to pass over or under tracks (bridges, culverts, flumes, sheds) • Ditch catchment
Deflecting the track rail surface,	• Rock falls, slides, topples	• Track geometry (curves and spirals are more susceptible) • Train loading • Track surface • Shoulder width • Ballast, sub ballast quality
Changing the track gauge	• Rock falls	• Track quality
Damaging the track components	• Rock falls	• Continuous welded vs. jointed rail • Concrete vs timber ties
Damaging track structures (such as bridges, retaining walls or sheds)	• Rock falls	• Location, shape, orientation, and foundation type of bridge piers and abutments. • Type of retaining wall (Tie-back, cantilever, gravity) • Location, shape, orientation, capacity, abrasion protection and foundation type of rock or snow sheds.

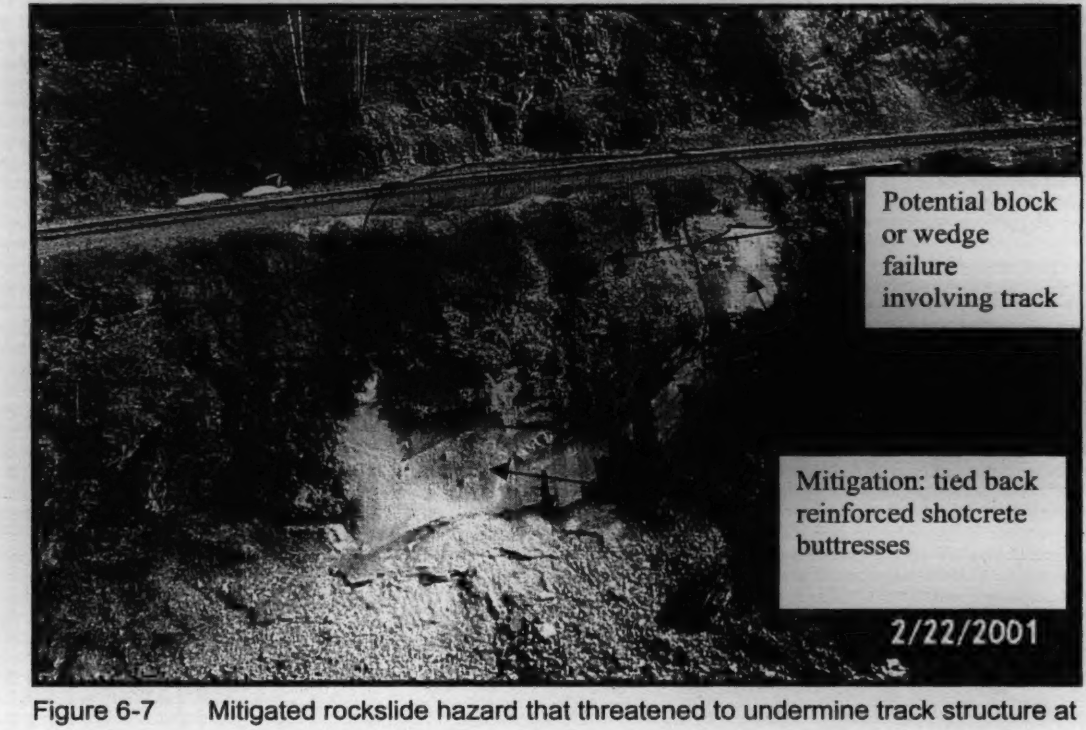

Potential block or wedge failure involving track
Mitigation: tied back reinforced shotcrete buttresses
2/22/2001

Figure 6-7 Mitigated rockslide hazard that threatened to undermine track structure at Mile 16.4 CN Yale Subdivision (Photo by Tim Keegan, ref CN File 4670-YLE-16.7)

6.10.2 Service Disruption Vulnerability

The primary service disruption vulnerability factors for Rock landslide scenarios given that track failure has occurred, include presence or absence of warning devices such slide detector fences, train speed, sight lines, grades, presence or absence of central traffic control circuit in the tracks. and traffic frequency. More details on these factors is given in Section 4.6.2.

6.10.3 Derailment Vulnerability

The primary derailment vulnerability factors for Rock landslide scenarios, given that track failure has occurred, include presence or absence of warning devices such slide detector fences, train speed, sight lines, grades, presence or absence of central traffic control circuit in the tracks. and traffic frequency. More details on these factors is given in Section 4.6.3.

6.11 Summary

From Chapter 3, accidents attributable to rock landslides, predominantly rock falls, occurred at an average frequency of 2.4 per year, with a severity of $63,000 direct costs per accident, accounting for $150,000 per annum, occurring mainly on the CN Edmonton to Vancouver corridor.

This chapter steps through the characterization of the identified rock landslide hazard scenarios from the CN Western Canada ground hazard database that would have attributed to these loss records.

The vast majority, 99.5%, are classified as simple rock fall scenarios and the remaining 0.5% are classified as simple rock slide scenarios. In Rock fall scenarios, after detachment, the particles fall, bounce or roll to the tracks and cause track failure by blocking the track, striking a train or equipment, deflecting the track, or damaging the track components. It is likely that a significant number of these scenarios actually have rock slides or rock topples as the initiating event, however it is not possible to determine this from the existing records. Rock slide scenarios identified initiate with a rock slide from under the tracks which causes track failure by either deflecting the track surface or by removing support from the track structure.

Ground conditions and processes associated with rock landslide events involve down slope movement from intact rock which either falls, topples or slides. The initial failure processes are controlled by the discontinuities in the rock mass. A fall is defined as the descent of the particle by free fall (slopes steeper than 76°), bouncing(slopes between 45° and 76°) or rolling (slopes less than 45°). A rock fall event may involve the displacement of a single fragment or many. It commonly begins by detachment of a more or less coherent block that fragments along its trajectory. A rock topple occurs when a rock mass rotates about a point or axis located below the centre of gravity of the displaced mass occurring when the discontinuities dip steeply into the slope. Toppling can be driven by gravity or from water or ice in cracks in the mass. The more common modes of toppling are block toppling, flexural toppling, chevron toppling or any combination of these. Toppling processes are characteristically slow or small incremental movements and commonly precede rock falls or rock slides. Rock slides involve shear strain or displacement across adversely oriented discontinuities or weak layers. Common types of movement include planar, wedge or rotational failure. Rock slides are commonly the initiating hazard event preceding a rock fall or a dry debris flow.

The observed rates of rock fall movement are very rapid to extremely rapid, and may or may not be preceded by minor movements. Rock Slides range from slow to very rapid.

Timing of rock falls depends, as expected, on the trigger causal factors, specifically freeze and thaw cycles, but also coincident with intense rain, heavy snow melt or rapid root growth.

Rock landslides tend to occur suddenly; in remote locations and preparatory process causal factors are constantly at work. As a result, rock fall hazards tend to remain in a (3) track stability state requiring periodic monitoring in the form of inspections. At CN this is managed by the CN RHRA (Pritchard et al, 2005) quantitative risk assessment system.

Observed preparatory causal factors for rock falls are not systematically recorded in the CN RHRA database and thus none are reported in this thesis. For rock slide scenarios, piping erosion, seepage erosion, slope wash erosion and shoulder sloughing were identified as preparatory causal factors.

Suggested preparatory causal factors for rock landslides include:

Ground Conditions:

- Weak materials
- Weathered materials
- Sheared materials
- Jointed or fissured materials
- Adversely oriented mass discontinuity
- Adversely oriented structural discontinuity
- Contrast in permeability
- Contrast in stiffness
- Large source volumes
- Adverse fragment sizes
- Steep slope
- Long slope
- Channelized slopes
- Absence of barriers

Geomorphological Processes

- Tectonic or volcanic uplift
- Glacial rebound
- Glacial over steepening
- Fluvial erosion of slope toe
- Wave erosion of slope toe
- Subterranean erosion
- Vegetation removal

Physical Processes

- Low level Intense snow melt
- Significant antecedent rainfall
- Earthquake
- Volcanic eruption
- Thawing
- Frost wedging
- Freeze-and-thaw weathering
- Shrink and swell weathering
- Chemical weathering
- Vegetation
- Water pressure in discontinuities

Man-made or animal processes

- Excavation of rock slope at its toe
- Over steepening
- Excessive blasting
- Loading of slope on its crest
- Ineffective mitigation
- Vegetation removal
- Irrigation
- Irrigation
- Water leakage from utilities
- Blocked drainage

The predominant observed trigger causal factors in all categories include intense rain, significant antecedent rain (SAR), daily freeze-thaw cycles, snow melt, raising freezing level, and thaw. The common factor is the introduction of free water into the rock discontinuities which increases water pressure, flow erosion or ice jacking potential.

A rock slide-rock fall case example from Mile 5.3 of the CN Yale Subdivision is presented to illustrate the combined effect of simultaneous trigger causal factors which in this case included intense snow melt, intense rain, significant antecedent rain, rain on snow and freeze-thaw. Not only did these combined process causal factors trigger a large rock fall they acted as preparatory causal factors by disturbing the surrounding rock mass making subsequent rock falls much more likely and bringing the track stability state for this rock fall hazard scenario to (2) marginally stable. Suggested trigger causal factors for rock landslides include:

Geomorphological Processes

- Fluvial erosion of slope toe
- Wave erosion of slope toe
- Subterranean erosion

Man-made or animal processes

- Excavation of rock slope at its toe
- Loading of slope on its crest
- Irrigation
- Water leakage from utilities
- Blocked drainage

Physical Processes

- Low level
- Intense snow melt
- Intense rainfall
- Significant antecedent rainfall
- Seepage erosion
- Earthquake
- Volcanic eruption
- Thawing
- Freezing
- Frost wedging
- Freeze and thaw
- Heavy snow fall
- Vegetation
- Wind Throw
- Water pressure in discontinuities

The relevant controlling attributes for rock fall hazard scenarios include geology, geomorphology, mitigation effectiveness, slope geometry, run-out distance and presence of barriers. The controlling laws are laws of gravity, inertia and rebound. The ability to predict rock fall behavior has been enhanced with the development of dynamic rock fall computer programs. Controlling attributes for remote natural rock slope source areas include run-out path location and distance, energy and spatial distribution at track level and fragmentation of the source rock. For rock topple or rock slide scenarios attributes include the relative position of the rock slope and the likelihood that the rock slide or topple will occur and affect the track, determined by the geology, geomorphology, river morphology, effectiveness of mitigation and slope geometry. Both 2-dimensional and 3-dimensional dynamic rock fall computer programs are applicable to the modeling of these attributes.

Rock landslide landforms occur as either natural or anthropogenic steep rock slopes or cliffs. The rock type and fabric of discontinuities controls the behaviour of a rock mass. Debris cones, fresh surfaces, dilatency, loose rocks, overhangs, adversely oriented discontinuities, pervasive discontinuities, toppling, seepage, icing and tree growth all indicate potentially active rock slopes.

Rock falls represent higher likelihood of track failure due to higher frequency, mobility and speed.

Rock landslide events cause track failure by removing support; blocking the track; striking trains; deflecting track surface, changing track gauge, damaging track structures or track components. Derailment hazard from a rock fall blocking the track increases with particle size, dimensions and shape, lack of deflection space, debris pile concentration, wedge or slab shaped particles and energy of impact.

Rock topples and rock slides cause track failure if they impede the train clearance or remove support from the track structure. Controlling factors include the relative position of the rock slope and the likelihood the event will affect the track determined by the geology, geomorphology, river morphology, effectiveness of mitigation and slope geometry. Table 6-7 lists track vulnerability factors in the vicinity of the track and a case example is provided.

Service disruption and derailment vulnerability factors for rock landslide scenarios depend on warning devices, train speed, sight lines, grades, central traffic control and traffic frequency.

Chapter 7 Characterization of Railway Debris Landslide Hazard Scenarios: CN Western Canada

7.1 Introduction

From the review of loss records presented in Chapter 3, between 1992 and 2002 train accidents attributable to debris landslides, predominantly channelized debris flow scenarios, occurred at an average frequency of 1.2 per year, with $170,000 in direct costs per accident, accounting for $200,000 per annum. The large majority of these incidents occurred on the CN Edmonton to Vancouver corridor near Mt.Robson, B.C. and Yale, BC.

This chapter steps through the characterization of the identified debris landslide hazard scenarios from the CN Western Canada ground hazard database that are attributed to these loss records. Following an illustration and description of the hazard scenarios initiating with debris landslides the chapter characterizes debris landslide ground conditions and processes, rates and timing of system failure and track stability states. This is followed by identification and characterization of debris landslide hazard scenario preparatory and trigger causal factors, either observed or interpreted by the author, followed by an identification of debris landslide controlling attributes. The chapter closes with a summary of debris landslide hazard scenarios consequence likelihood factors for track failure, service disruption and derailment.

7.2 Debris Landslide Hazard Scenarios FMEA.

The short list of identified hazard scenarios initiating with debris landslide events is presented in Table 7-1. Of the four scenarios in this group the majority, 70%, are classified as complex Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow scenarios and the remaining 30% are classified as either simple Debris Fall or Debris Slide scenarios or complex Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall scenarios. Following is an illustration and description of the FMEA for each of these.

Table 7-1 Summary of debris landslide hazard scenarios CN Western Canada

Level III	Ground Hazard Scenario	Coding	Count
Debris Landslides	**Debris Landslides**		
	Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow	DFw - Av – DFw / GE / SE / ESl - EFw -	31
	Debris Fall	DF -	9
	Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall	DSl - SE / GE - DF -	2
	Debris Slide	DSl -	2
	Subtotal		44

7.2.1 Debris Flow - Avulsion – Debris Flow / Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow Hazard Scenario

Figure 6-1 depicts a simplified FMEA for the Debris Flow - Avulsion – Debris Flow / Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow hazard scenario. This scenario usually initiates with a channelized debris flow which may or may not reach to the tracks. If it reaches the track it can cause track failure by track blockage, striking a train or striking a track support structure, most commonly a bridge. Often, the author observed the debris flow blocks or redirects the usual drainage course or plugs culverts or bridges, causing an avulsion of the water torrent which generally follows a channelized debris flow. The excessive, misdirected water can:

- Scour a new channel entraining debris resulting in a third order debris flow event and /or

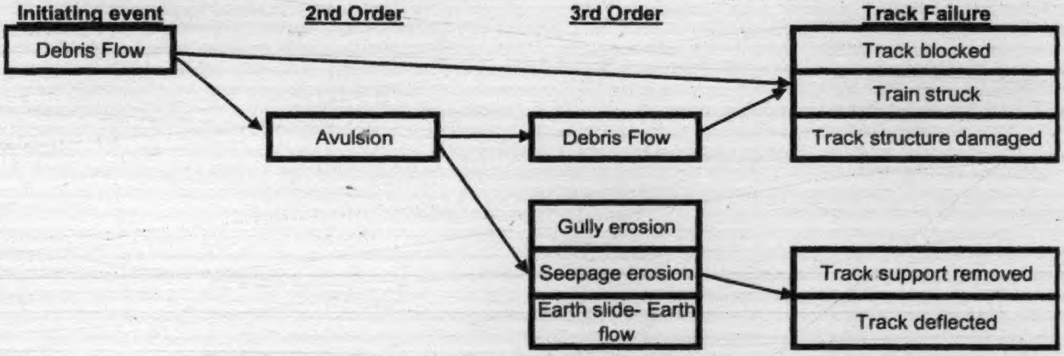
- Cross over or through the track grade, creating a gully erosion (Chapter 11), seepage erosion (Chapter 11), or earth slide –earth flow (Chapter 8) hazard.

These hazard events cause track failure by either removing track support or deflecting the track.

Debris Landslide Scenarios **Total count: 44**

Debris Flow - Avulsion - Debris Flow/Gully Erosion /
Seepage Erosion / Earth Slide - Earth Flow **Count 31**

DFw - Av - DFw / GE / SE / ESl - EFw -


Initiating event
2nd Order
3rd Order
Track Failure
Debris Flow
Avulsion
Debris Flow
Gully erosion
Seepage erosion
Earth slide- Earth flow
Track blocked
Train struck
Track structure damaged
Track support removed
Track deflected

Notes:
1. Primarily channelized debris flows from upstream of tracks
2. Avulsion results from debris redirecting or blocking water flow in channel, culvert or bridge
3. 3rd Order Debris flow results from new channel scour and entrainment from misdirected flow.
4. GE, SE or ESl-EFw result from misdirected water flow passing over/through the track grade

Figure 7-1 Simplified FMEA for the Debris Flow - Avulsion – Debris Flow / Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow hazard scenario

A case example of this scenario, in which the secondary and tertiary hazard events of avulsion and earth slide–earth flow occurred, is the derailment that occurred at Mile 10.3 of CN's Robson Subdivision on July 18, 2001 (CN file 4670-RBS-10.3). On this date, an intense rain fall event estimated at 100 mm in a 4 hour period, triggered a debris flow down the debris flow channel which normally passes under a bridge at Mile 10.1. The debris flow jumped its channel to the left, approximately 75 metres upstream of the bridge, due to a constriction in the channel. The debris flow itself tapered off in the forest however the ensuing water torrent flowed down the track ditch and infiltrated the track grade. On the down stream slope the greatly elevated phreatic surface and steep hydraulic gradient caused three earth slides- earth flows to initiate, causing track failure by removing support. The train traversed the first two earth slide-earth flow locations, but noticed a dip in the track and derailed at the third location. There were no culverts in this stretch between the bridge and the derailment and it was reported that the surface drainage had always soaked into the ground. The time delay between the debris flow and the track failure can not be determined with any certainty.

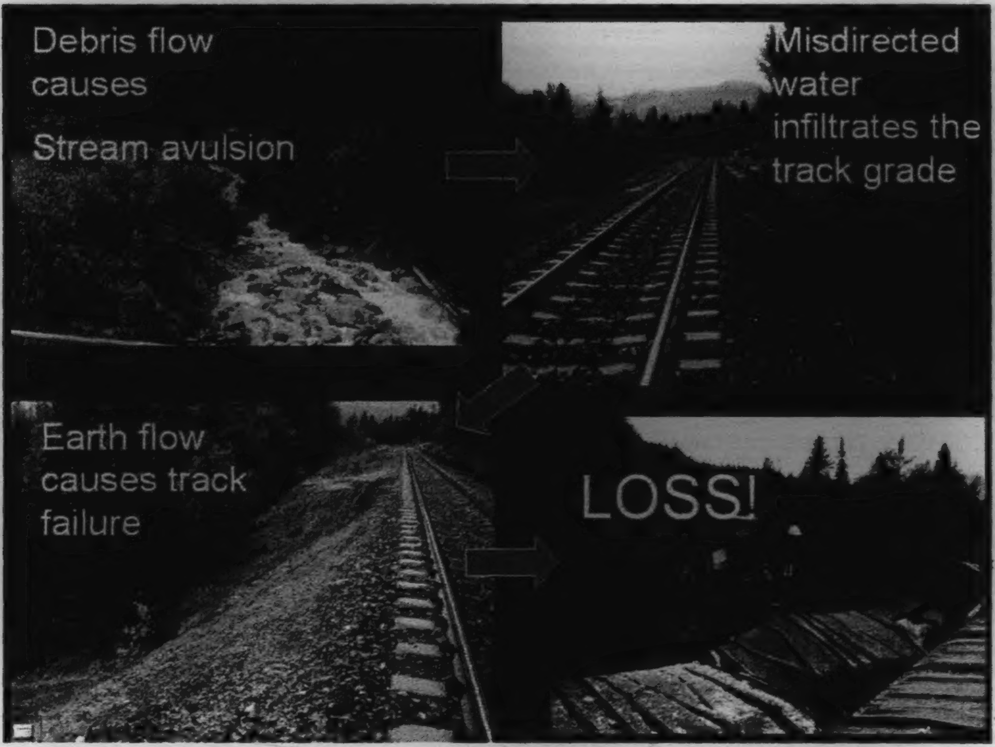
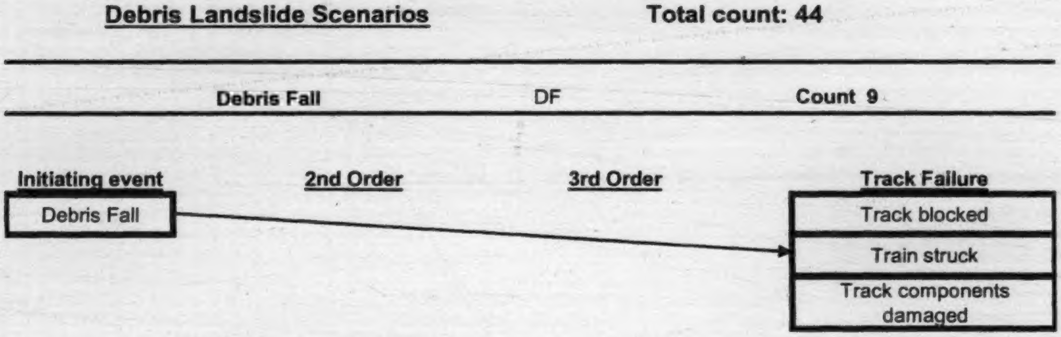

Debris flow causes
Stream avulsion
Misdirected water infiltrates the track grade
Earth flow causes track failure
LOSS!

Figure 7-2 Example of a Debris Flow - Avulsion – Debris Flow / Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow hazard scenario event that occurred on July 18, 2001 at Mile 10.3 of CN Robson Subdivision (Photos taken by Tim Keegan, CN file 4670-RBS-10.3)

7.2.2 Debris Fall Hazard Scenario

Figure 7-3 depicts a simplified FMEA for debris fall hazard scenario. These hazard scenarios involve debris size particles ranging in size from cobbles to large boulders that dislodge and fall, bounce or roll to the track. Track failure is realized if the particles of sufficient size or quantity end up on the track, strike a train or damage the track components. Processes such as slope wash, gully erosion, seepage erosion, thawing or wind will tend to erode smaller particles, causing the larger particles to dislodge.


Debris Landslide Scenarios
Total count: 44
Debris Fall
DF
Count 9
Initiating event
2nd Order
3rd Order
Track Failure
Debris Fall
Track blocked
Train struck
Track components damaged

Notes:
1. Debris falls from above
2. Debris particles dislodged by slope wash, gully or seepage erosion

Figure 7-3 Simplified FMEA for debris fall hazard scenario

Figure 7-4 depicts a typical debris fall hazard scenario at Mile 19.9 of CN's Clearwater Subdivision in BC (CN file 4670-CLR-19.9).

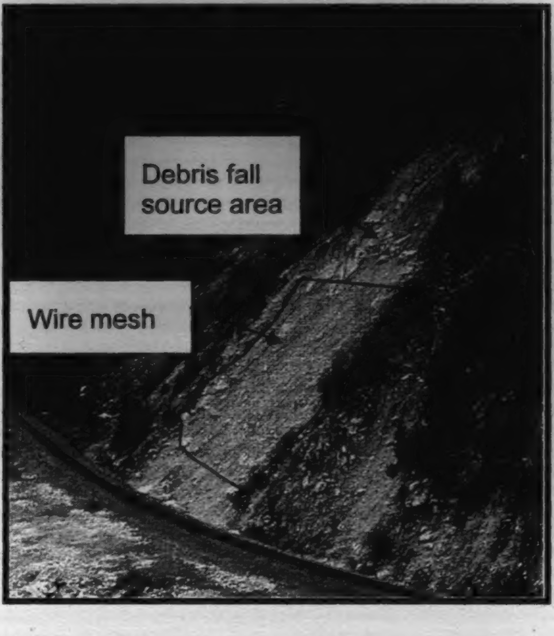
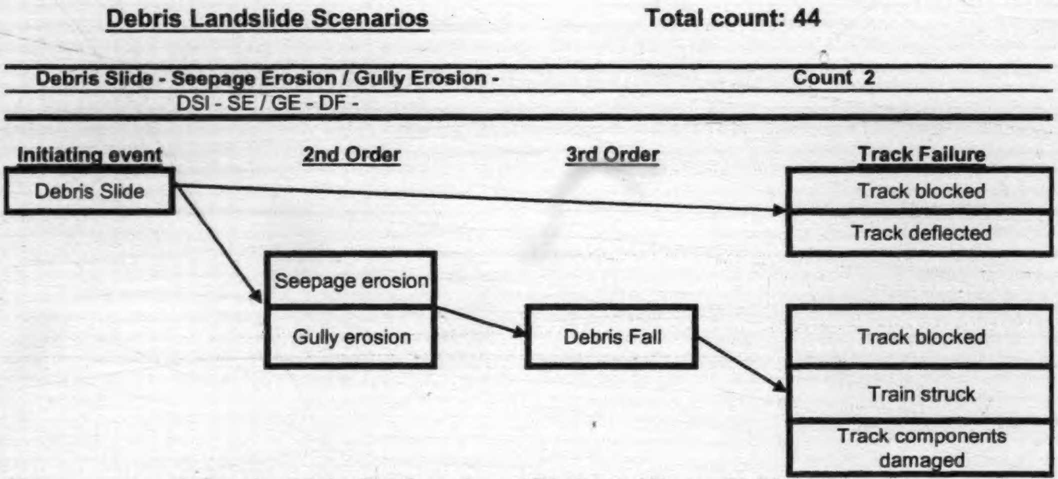

Debris fall source area
Wire mesh

Figure 7-4 Example of a debris fall hazard scenario Mile 19.9 CN Clearwater Subdivision (Photo by Tim Keegan, ref CN file 4670-CLR-19.9)

7.2.3 Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall Hazard Scenario

Figure 7-3 depicts a simplified FMEA for a Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall hazard scenario. There are two ground hazards in the database that share this scenario, which are in close proximity to each other, at Mileages 54.2 and 54.6 of CN's Albreda Subdivision near Mt. Robson, BC. In both cases relatively large debris slides have developed immediately uphill of the track at the toe of a much larger debris flow cone. The material in the slide ranges from a fine grained low plastic but micaceous matrix up to large boulders several metres in diameter. The debris slides appear to move slowly and intermittently, triggered by increases in the phreatic surface. Although the debris flows toe out above the track, the toe bulge periodically infringes into the train clearance envelope, which results in track failure from blockage or by deflecting the track surface. The second and third order hazard events involve seepage erosion and gully erosion on the slope that serves to erode out the fine grained matrix dislodging the larger debris particles, resulting in the debris fall hazard. Track failure is realized if the particles of sufficient size or quantity end up on the track, strike a train or damage the track components.


Debris Landslide Scenarios
Total count: 44
Debris Slide - Seepage Erosion / Gully Erosion -
Count 2
DSI - SE / GE - DF -
Initiating event
2nd Order
3rd Order
Track Failure
Debris Slide
Track blocked
Track deflected
Seepage erosion
Gully erosion
Debris Fall
Track blocked
Train struck
Track components damaged

Notes:
1. Creeping debris slides from above. (CN Albreda Mileages 54.2 & 54.6)
2. SE or GE the result of over steepened slope above tracks from debris slide
3. Debris falls from above reaching the track

Figure 7-5 Simplified FMEA for Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall hazard scenario

An example of this scenario at Mile 54.2 of the CN Albreda Subdivision is illustrated in Figure 7-6. Despite substantial efforts to mitigate this scenario, it continues to move intermittently, marked by frequent debris falls into the railway ditch. There is some suggestion that the entire debris cone above this location may be moving as a very slow debris flow however this has yet to be substantiated.

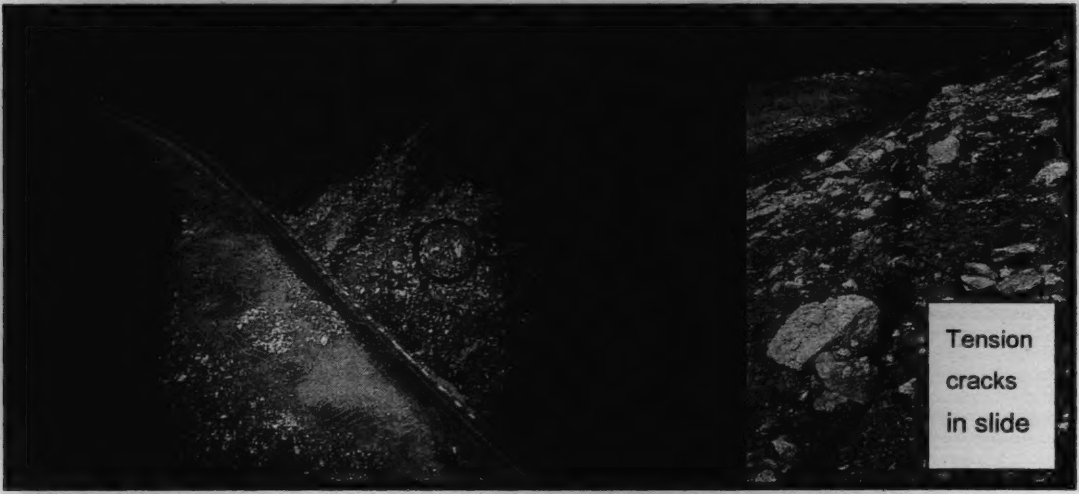


Figure 7-6 Example of Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall hazard scenario (the moonscape) Mile 54.2 CN Albreda Subdivision (Photos by Tim Keegan, Ref. File 4670-ABD 54.2)

7.2.4 Debris Slide

Figure 7-7 depicts a simplified FMEA for a debris slide hazard scenario. The two locations where this scenario was identified involve debris slides on a shallow sloping bedrock surface from above the track. These scenarios can cause track failure if particles of sufficient size or quantity end up on the track, strike a train or damage the track components.

A review of the records indicate that this scenario initiates with a rock slide from under the tracks which causes track failure by either deflecting the track surface or by removing support from the track structure.

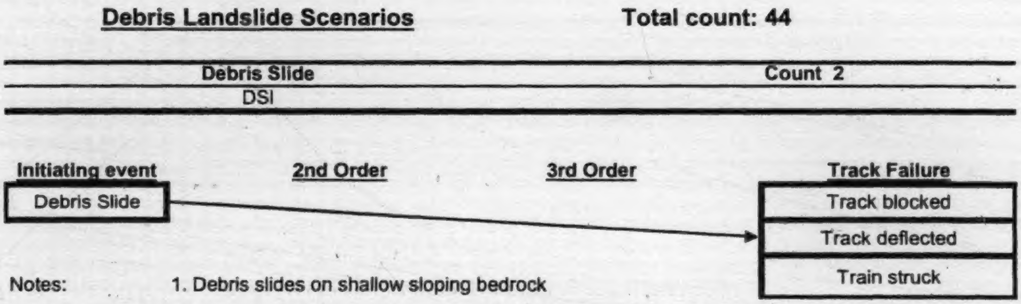

Debris Landslide Scenarios
Total count: 44
Debris Slide
Count 2
DSI
Initiating event
2nd Order
3rd Order
Track Failure
Debris Slide
Track blocked
Track deflected
Train struck
Notes:
1. Debris slides on shallow sloping bedrock

Figure 7-7 Simplified FMEA for the debris slide hazard scenario

7.3 Debris Landslide Hazard Events Ground Conditions and Processes

The debris material type refers to a soil that contains a significant proportion of coarse material; 20 to 80 percent are larger than 2 mm, the remainder is less than 2 mm (Cruden and Varnes, 1996). The three main types of debris landslide are debris fall, slides and flows. The ground conditions and processes associated with each of these are described in the following sections.

7.3.1 Debris Falls– Ground Conditions and Processes

A debris fall occurs when one of more pieces of debris are detached from a steep slope along a surface on which little or no shear displacement takes place, and descends by free fall, bouncing or rolling with minimal inter-particle interaction. Similar to rock falls, observations show that free fall generally occurs when the slope below the debris fall source exceeds 76°, bouncing occurs on slopes at less than this angle and rolling occurs on slopes with angles less than 45° (Cruden and Varnes, 1996).

Detachment can result from either weathering and erosional processes undermining larger particles or by changes to the slope geometry that over-steepens the slope. Erosion or weathering processes, including overland and/or through flow erosion, wind, freeze and thaw and train action, act to remove finer more easily eroded particles leaving a coarse grained rough surface which eventually results in debris particle detachment. Over-steepening, beyond the angle of repose, can be caused by removal of material at the toe or sliding within the debris slope. Debris falls are often referred to as raveling. Movements are very rapid to extremely rapid, and may or may not be preceded by minor movements.

7.3.2 Debris Slides- Ground Conditions and Processes

Debris slide movements have a defined rupture surface or thin zones of intense shear, that can be rotational, translational or compound in mode, and are usually controlled by the weaker matrix soil, elevated pore pressures, sloping bedrock, bedding, weak layers or remnant discontinuities, in the case of residual soils. They slide as long as the sliding mass maintains its cohesion. Movements are very slow to very rapid, dependent on the material along the rupture surface. Very slow debris slides require sufficient portions of fines such as silt and clay along their rupture surfaces and adequate moisture to lower the effective stresses and sustain the movements.

7.3.3 Debris Flow - Ground Conditions and Processes

A debris flow is a landslide that occurs in debris, resembling the movements of a viscous fluid. The velocity is greatest at the surface and decreases downward in the flowing mass. Cruden and Varnes (1996) stated that the lower boundary of the displaced mass may be a surface along which appreciable differential movement has taken place or along a thick zone of distributed shear. There is a gradation in the definition of slides to debris flows, in both debris and rock, depending on water content, mobility and evolution of the movement. Debris flows are often of high density, with over 80% solids by weight, and may exceed the density of wet concrete (Hutchinson,1988).

Open-slope debris flows form their own path down a valley side onto gentler slopes at the foot.

Channelized debris flows, also referred to as debris torrents, follow existing channels. Key hazard characteristics of channelized debris flows include their mobility and the length and spatial fluctuation of their flow paths. Hungr et al (1984) aptly described the nature of channelized debris flows in Western Canada as follows:

> "Debris torrents begin in the steep upper reaches of small drainage basins during periods of high runoff, collecting large quantities of loose material from the entire length of the channel and depositing on the surface of the debris cone. Two or more branches of a given stream may be involved in a single event. Many debris torrent events occur in two or more surges, spaced over several hours. Individual

> surges have short durations measured only in minutes, and are commonly associated with abundant water flooding.
>
> A typical surge through the lower reaches of a mountain creek begins by the rapid passage of a steep boulder front, followed by the main body of the torrent. This consists of unsorted coarse particles ranging from gravel to boulders and logs, floating in slurry of liquefied sand and finer material. Both the proportion of fines and the water content increase in the later stages of the surge, forming a liquid "after flow", which gradually merges into normal flood flow. Upon reaching flatter gradients or a less confining channel, the surge tends to decelerate and deposition can occur. The liquid after flow may break through the coarse deposits and continue further down the cone."

Similar channelized debris flow events were experienced along CN's rail corridor between Hinton and Vancouver. These events occur frequently with occasionally serious consequences. Figure 3.7 illustrates two such examples of channelized debris flow hazards at Mile 53 to 55 CN Albreda Subdivision on the slopes of Mount Klapperhorn (CN File 4670-ABD-53-55, Davies, 2007) and at Mile 24.8 CN Yale Subdivision in the lower Fraser River Valley(CN File 4670-YLE-24.8). Preceding a major event at Mile 24.8 Yale in June 1999, a large rock slide occurred at the crest of the upper source and the channel above the apex was occupied by snow avalanche debris. These are felt to be significant preparatory causal factors for the event.

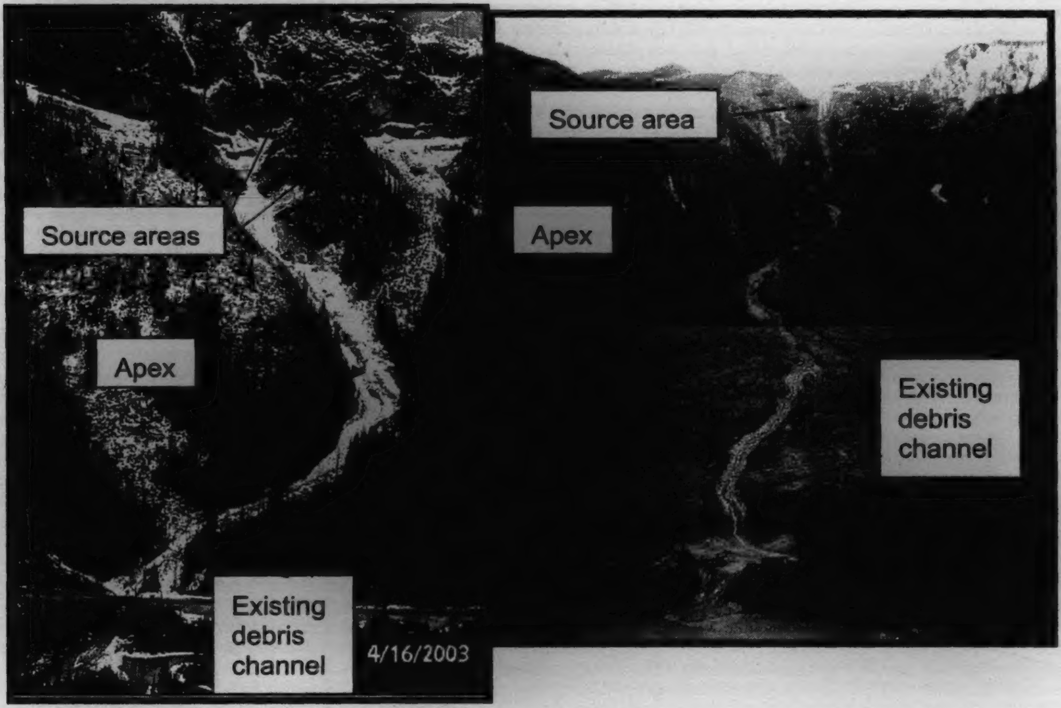

Source areas
Apex
Existing debris channel
4/16/2003
Source area
Apex
Existing debris channel

Figure 7-8 Examples of channelized debris flow hazards at Mile 54.3 Albreda CN Subdivision near Mt. Robson (left photo, by Tim Keegan, ref file 4670-ABD-54.3) and Mile 24.8 CN Yale Subdivision near Yale B.C. (right photo by Iain Bruce, ref file 4670-YLE-24.9)

7.4 Debris Landslide Hazard Scenarios Rates of Ground Hazard System Failure

Table 6-2 presents a summary of the subjectively estimated rates of track failure recorded by the author for the CN Western Canada debris landslide hazard scenarios. In general terms, when the ultimate event in the scenario involves a slide or flow, the rates of track failure range from moderate to rapid and when the ultimate event involves a fall, it is rapid to very rapid.

Table 7-2 Rates of tracks failure from debris landslide hazard scenarios

				Percentage of Ground Hazards Reporting this Speed				
Level III Subgroups	**Ground Hazard Scenario**	**Coding**	**Count**	**Very Rapid**	**Rapid**	**Moderate**	**Slow**	**Very Slow**
Debris Landslides	**Debris Landslides**							
	Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow	DFw - Av - GE / SE / ESI - EFw -	31	3%	35%	13%	6%	6%
	Debris Fall	DF -	9	11%	33%	0%	11%	22%
	Debris Slide - Seepage Erosion / Gully Erosion Debris Fall	DSI - SE / GE - DF -	2	0%	50%	50%	0%	0%
	Debris Slide	DSI -	2	0%	50%	0%	0%	50%
		Subtotal	**44**	**5%**	**36%**	**11%**	**7%**	**11%**

Timing of debris landslides are dependent mainly on the trigger causal factors; specifically intense rain, antecedent rain and heavy snow melt. Time lags between hazard events associated with the Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow and the Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall hazard scenarios can range from minutes to months. In the latter scenario, the debris sliding usually occurs in mid to late spring, weeks or months following snow melt whereas the debris falls coincide mostly with the thawing of ground ice in early spring (see Figure 7-9). In addition, channelized debris flows often occur in multiple events separated by minutes or hours, and caution should be used when entering the area following a debris flow event.

7.5 Debris Landslide Hazard Scenarios Track Stability States

The majority of the channelized debris flow scenario sites are associated with infinite source areas, which are inaccessible and impractical to mitigate. As a result these scenarios for the most part remain in the (3) Stable – monitoring required track stability state or lower. Scenarios involving debris falls may be effectively mitigated using barriers, ditch cleaning or debris sheds, however unless avoidance is considered, monitoring would still be necessary as preparatory causal processes continue to exist.

7.6 Debris Landslide Hazard Scenarios Preparatory Causal Factors

7.6.1 Observed Debris Landslides Preparatory Causal Factors

Error! Reference source not found. presents the preparatory causal factors recorded for each debris landslide hazard scenario according to the categories of erosion, poor drainage, beaver activity, landslide material, landslide movement type and other observations. The percentage each preparatory causal factor was reported for each hazard scenario is presented in brackets.

For Debris Flow- Avulsion - Gully Erosion / Seepage Erosion / Earth Slide – Earth Flow scenarios, the only significant preparatory causal factors recorded include a propensity for stream shifts and for new streams to form, and recognition that bridge erosion is a significant preparatory causal factor to heighten the hazard level of this scenario. Other preparatory causal factors identified by the author for this complex hazard scenario include evidence of frequent debris flows and avulsions, potential for new streams, blocked or insufficient drainage or bridge clearance, high bed loads or debris laden channels.

For Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall hazard scenarios, slope wash and seepage erosion were identified as significant preparatory causal factors for the debris fall hazard event in the scenario.

Preparatory Causal Factors: CN Western Canada Railway Ground Hazard Scenarios

Level III Subgroups	Ground Hazard Scenario	Count	Erosion	Poor Drainage	Beaver Activity	Landslide Material	Landslide Movement Type	Other Observations
Debris Landslides	**Debris Landslides**							
	Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow	31	Piping (10%),Slope (13%),Seepage (19%),Ditch (19%),Stream (13%),Bridge (23%),Inlet (19%),Outlet(3%),River(3%),	Partially(6%),Blocked(10%),Poor Inlet(3%),Stream Shift(35%),New Stream(26%),Anthro(3%),		Rock(13%),Debris(100%),Earth(3%),Snow(6%),	Fall(13%),Slide(13%),Flow(100%),	Damaged Structure(6%),
	Debris Fall	9	Slope (11%),			Debris(100%),Earth(22%),Earth Fine(33%),Earth Cohesive(11%),	Fall(100%),Slide(11%),Flow(22%),	
	Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall	2	Slope (100%),Seepage (50%),	HWT(50%),Rapid Drawdown(50%),		Debris(100%),	Fall(100%),Flow(100%),	
	Debris Slide	2				Debris(100%),	Slide(100%),	
	Subtotal	**44**	Piping (7%),Slope (16%),Seepage (16%),Ditch (14%),Stream (9%),Bridge (16%),Inlet (14%),Outlet(2%),River(2%),	cked(7%),Poor Inlet(2%),Ponding or HWT(2%),Stream Shift(25%),New Stream(18%),Rapid		Rock(9%),Debris(100%),Earth(7%),Earth Fine(7%),Earth Cohesive(2%),Snow(5%),	Fall(34%),Slide(16%),Flow(80%),	Damaged Structure(5%),

Table 7-3 Preparatory causal factors identified for each debris landslide hazard scenario grouped into erosion, poor drainage, beaver activity, landslide material, landslide movement type and other observations. The percentage each preparatory causal factor was reported for each hazard scenario is presented in brackets.

Recent experience by the author (see Figure 7-9) indicates that thawing ground frost is a significant causal factor for debris falls, indicating that ground frost in debris slopes is also a significant preparatory causal factor for debris falls.

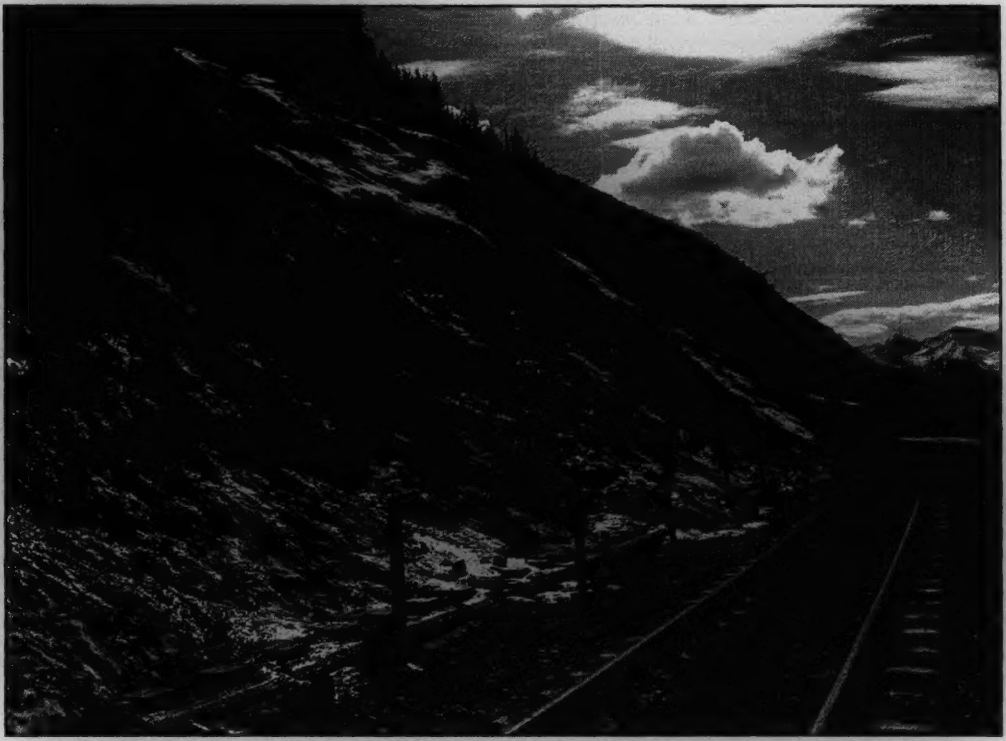


Figure 7-9 Example of ground frost, a preparatory causal factor, melting and triggering debris falls at Albreda Subdivision Mile 54.55 (Photo by Tim Keegan taken April 4, 2006).

7.6.2 Suggested Debris Landslides Preparatory Causal Factors

Several preparatory causal factors account for the difficult nature of debris landslides to the Canadian railways particularly through the Western Cordillera. In Canada, Quaternary glaciations, followed by postglacial down cutting of river systems, has resulted in a significant amount of primary source mass wasting and generation of a significant quantity of debris. Similar to rock landslide hazard scenarios, debris landslide hazard scenarios are inherently more common along railways in high relief terrain due to gradient and curvature restrictions. In Table 7-4 the author provides a suggested glossary of the preparatory causal factors for debris landslides.

Table 7-4 Preparatory causes of Railway Debris Landslide Hazards

Preparatory Causal Factors – debris landslides		Description
1.Ground Conditions		
QGM	Quaternary Glaciation Material	Quaternary glacial, glacial fluvial or post glacial fluvial erosion resulting in significant morainal and fluvial debris deposits and steep natural slopes leading to the accumulation of debris deposits in the transportational midslope (unit 5, **Error! Reference source not found.**) or directly cause debris slide and fall hazards (see Figure 7-4).
CP	Contrast in permeability	Causes build up of water pressures and seepage forces above interface, resulting in reduced effective stress and shear strength, and increases in thrust forces. Preferred flow paths and increased seepage forces cause internal erosion and concentrated seepage erosion from the slope. Promotes ice wedging by providing abundant free water.
CS	Contrast in stiffness	Boundary formed by loose unconsolidated debris deposits over stiff, dense or cohesive materials such as bedrock or consolidated deposits, introduces potential sliding surface, causing a debris slide hazard.
2.Geomorphological Processes		
ARS	Active rock fall source	Provides source for accumulation of unsorted unconsolidated debris in the transportational midslope (unit 5, **Error! Reference source not found.**) causing debris landslide hazards.
AAS	Active avalanche source	Provides source for accumulation and channel blockage of saturated, unsorted and unconsolidated debris from snow avalanches causing a debris landslide hazard (see Figure 7-8).
GI	Glacial	Current glacial, glacio-fluvial or glacio-lacustrine processes causing accumulation of debris, blockage of natural drainage, build up of water or erosion causing a debris landslide hazard.

Preparatory Causal Factors – debris landslides		Description
FET	Fluvial erosion of slope toe	Ongoing or periodic stream erosion of debris slopes below and above the tracks causing over-steepening .
WET	Wave erosion of slope toe	Ongoing and periodic wave erosion of debris slopes below tracks causing over-steepening.
SE	Subterranean erosion	Material can be removed from below by solution or piping affectively loosening the debris deposit and may increase the debris landslide hazard
VR	Vegetation removal	Removal of vegetation by natural means such as forest fire, drought, wind or previous debris flows can increase water infiltration, removing the stitching effect of roots and decreasing evapotranspiration.
3.Physical Processes		
LLISM	Low level intense snow melt	Provides rapid recharge of water into the debris in proximity of the track reducing effective stress and shear strength. As a preparatory cause a time lag is associated with the snow melt event.
HLISM	High level intense snow melt	Provides rapid infiltration of water into the debris reducing effective stress and shear strength or rapid runoff and flash floods at upper levels. As a preparatory cause a time lag is associated with the snow melt event.
SAR	Significant antecedent rainfall	Causes an abundance of free water saturating debris causing water pressure build up reducing effective stress and shear strength, increasing the debris landslide hazard. As a preparatory cause the antecedent rainfall only brings the slope closer to failure.
IR	Intense rainfall	Causes an abundance of free water saturating debris, causing water pressure build up, reducing effective stress and shear strength, increasing the debris landslide hazard. As a preparatory cause the intense rainfall only brings the slope closer to failure.
HGR	High groundwater recharge	Causes a build up of water pressures and steepens the hydraulic gradient in the debris deposit resulting in reduced effective stress, thrust forces and high seepage forces increasing the debris landslide hazard.

Preparatory Causal Factors – debris landslides		Description
VE	Volcanic eruption	Seismic activity associated with a volcanic eruption from a nearby active volcano, may play a role as a preparatory cause by loosening the debris mass incrementally.
T	Thawing	Thawing of debris deposits inwards on slope resulting in reduction in negative pore pressures and saturation in the slope causing a debris landslide hazard. Thawing of ground frost on a debris slope results in solifluction and removal of fines from around debris particles preparing them for detachment. Also can provide free water for frost wedging of coarse debris.
FW	Frost wedging	Also known as ice jacking, is caused by the expansion of water turning to ice during freeze-thaw cycles. As a preparatory cause it serves to loosen cobble and boulder debris sizes causing a debris fall hazard (ravelling).
FT	Freeze-and-thaw weathering	Debris or the debris matrix may disintegrate, losing shear strength under cycles of freezing and thawing or thermal expansion and contraction, leading to undermining of coarser debris causing a debris fall hazard (ravelling).
WD	Wet and drying weathering	Cycles of wet and dry may cause loss of suction in unsaturated zone of non-cohesive debris matrix, leading to undermining of coarser debris, causing a debris fall hazard (ravelling).
SS	Shrink and swell weathering	Cycles of wet and dry may cause desiccation of a clay rich debris matrix leading to undermining of coarser debris causing a debris fall hazard (ravelling).
CW	Chemical weathering	Reduced strength of debris matrix due to chemical weathering undermining coarser debris causing a debris fall hazard (ravelling).
WE	Wind erosion	Wind removal of finer material undermining coarser debris causing a debris fall hazard (ravelling).
V	Vegetation	Roots prying out debris cracks causing a debris fall hazard (ravelling).

Preparatory Causal Factors – debris landslides		Description
4.Man-made or Animal Processes		
OS	Over steepening	Excavation of debris slopes impose an additional artificial over-steepening of already over-steepened natural debris slopes.
SOL	Shoulder over loading	Placement of waste debris on track roadbed shoulder or dumped over bank increases loading on the debris slope and over-steepens the slope increasing the destabilizing forces and potentially blocks seepage bringing the slope closer to failure.
VR	Vegetation removal	Deforestation or vegetation denudation of upper slopes and rock slopes increases infiltration of water into the groundwater, reduces evapotranspiration and suction provided by the trees and plants.
Ir	Irrigation	Increases groundwater recharge to the debris slope resulting in reduced effective stress. Thrust forces bring the rock slope closer to failure in the form of a rock landslide.
WLU	Water leakage from utilities	Increases groundwater recharge to the debris slope resulting in reduced effective stress. Thrust forces bring the debris slope closer to failure in the form of a debris landslide.
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can increase groundwater recharge to the debris slope resulting in reduced effective stress. Thrust forces bring the debris slope closer to failure in the form of a debris landslide.
BA	Beaver activity	Beaver habitat in the vicinity of the tracks predisposes the track to the processes of beavers, increasing the debris flow hazard by the collection of woody debris and the blockage of the channel upstream of the tracks.

7.7 Debris Landslide Hazard Scenarios Trigger Causal Factors

7.7.1 Observed Debris Landslide Hazard Scenario Trigger Causal Factors

Error! Reference source not found. presents the trigger causal factors identified for each debris landslide hazard scenario. As a group, the most frequently recorded trigger causal factors include intense rain, prolonged or significant antecedent rain (SAR), and snow melt. A summary of all the prevalent trigger causal factors for each debris landslide scenario is presented in Table 7-6.

For rapid channelized debris flows, the triggering causal factors generally need to result in high concentrated water flows down relatively confined channels. Thus triggers for these usually involve rapidly changing climatic conditions such as intense rain, rapid snow melt or rain on snow. Although not identified, non-climatic trigger causal factors such as landslide dam bursts, beaver dam bursts or uncontrolled anthropogenic drainage have also been known to trigger debris flows. Again, debris flows are much more likely to occur when two or more of these trigger causal factors act simultaneously. Rain on snow coupled with a rapid rise in the freezing level is considered a significant trigger causal factor for these events.

Trigger Causal Factors: CN Western Canada Railway Ground Hazard Scenarios

Level III Subgroups	Ground Hazard Scenario	Count	Intense Rain	Prolonged Rain	High Water	High Water Table	Piping	Freeze/Thaw	Snow Melt	Raising Freezing Level	Rapid Drawdown	Heavy Snow	Thaw	Anthropogenic	Train Action
Debris Landslides	**Debris Landslides**														
	Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow	31	77%	39%	10%	3%	0%	0%	74%	42%	0%	3%	3%	0%	0%
	Debris Fall	9	67%	56%	0%	89%	11%	33%	56%	11%	0%	0%	89%	0%	0%
	Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall	2	50%	100%	0%	50%	50%	100%	100%	50%	0%	0%	50%	0%	0%
	Debris Slide	2	50%	100%	0%	0%	0%	0%	50%	100%	0%	0%	0%	0%	0%
	Subtotal	44	73%	48%	7%	23%	5%	11%	70%	39%	0%	2%	23%	0%	0%

Table 7-5 Trigger causal factors identified for each debris landslide hazard scenario identified. The percentage each trigger causal factor was reported for each hazard scenario and each hazard scenario grouping is presented.

Table 7-6 Summary of prevalent debris landslide trigger causal factors observed according to the commonly identified Level IV debris landslide hazard scenarios.

Level IV Debris Landslide Hazard Scenarios	Prevalent Trigger Causal Factors Recorded	
Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow	• Intense rain • Snow melt • Raising freezing level	• Significant antecedent rain • Rain on snow*
Debris Fall	• Intense rain • Significant antecedent rain • Elevated phreatic surface • Snow melt	• Rain on snow* • Raising freezing level • Frost thaw
Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall	• Intense rain • Significant antecedent rain • Raising freezing level	• Freeze thaw, • Snow melt • Rain on snow* • Frost thaw
Debris Slide	• Intense rain • Significant antecedent rain • Raising freezing level	• Freeze thaw, • Snow melt • Rain on snow*

* Inferred trigger causal factor given that both intense rain and snow melt are identified

7.7.2 Suggested Debris Landslide Scenario Trigger Causal Factors

In Table 7-7 the author provides a suggested glossary and description of the trigger causal factors for debris landslide events.

Table 7-7 Preliminary railway debris landslide hazard trigger causal factors

Trigger Causal factors – debris landslides		**Description**
1.Geomorphological Processes		
FET	Fluvial erosion of slope toe	Ongoing and periodic stream erosion of debris slopes below tracks.

Trigger Causal factors – debris landslides		**Description**
WET	Wave erosion of slope toe	Ongoing and periodic wave erosion of debris slopes below tracks.
SE	Subterranean erosion	Material can be removed from below by solution or piping effectively loosening the debris mass and may trigger a debris landslide event.
2.Physical Processes		
LLISM	Low level Intense snow melt	Causes an abundance of free water to erode and undermine the debris slope, infill cracks causing water pressure build up, reduction in effective stress and potentially frost wedging.
IR	Intense rainfall	Causes an abundance of free water to erode and under mine the debris slope and infill cracks causing water pressure build up and reduction in effective stress, triggering a debris landslide.
SAR	Significant antecedent rainfall	Causes an abundance of free water to infill cracks causing sustained water pressure build up and reduction in effective stress triggering a debris landslide.
SE	Seepage erosion	Erosion due to seepage from a debris slope can undermine the slope and trigger a debris landslide.
EQ	Earthquake	Cyclic loading can trigger a debris landslide event when a debris landslide hazard exists.
VE	Volcanic eruption	Siesmic activity associated with a volcanic eruption may play a role as a preparatory cause by loosening the debris mass incrementally
T	Thawing	Thawing of debris deposits inwards on slope resulting in reduction in negative pore pressures and saturation in the slope triggering a debris landslide hazard. Thawing of ground frost on a debris slope results in solifluction and removal of fines from around debris particles triggering detachment. Also can provide free water for frost wedging of coarse debris.
F	Freezing	Onset of ambient freezing temperatures can cause frost wedging to occur.

Trigger Causal factors – debris landslides		Description
FW	Frost wedging	Also known as ice jacking is caused by the expansion of water turning to ice during freeze-thaw cycles. As a trigger cause it serves to open cracks triggering the debris landslide. Effect is enhanced when there is a negative temperature gradient into the debris whereby the unfrozen free water at the surface encounters debris at temperatures less than -3°C. This occurs predominantly in late winter due to the availability of free water from snow melt but can occur at other times when free water is available I.e. irrigation, groundwater springs etc.
FT	Freeze and thaw	Debris may disintegrate losing shear strength under cycles of freezing and thawing or thermal expansion and contraction. (Cruden and Varnes, 1996). This can trigger a debris landslide.
V	Vegetation	Often a debris fall is brought to failure by roots prying open cracks.
WPD	Water pressure in discontinuities	Causes a build up of water pressures in the debris mass resulting in reduced effective stress and increased thrust forces triggering a debris landslide.
3.Man-made or Animal Processes		
ET	Excavation of debris slope at its toe	Excavation or blasting of a debris slope at the toe can result in daylighting adversely oriented discontinuities triggering a debris landslide event
LSC	Loading of slope on its crest	Waste dumps, embankments or structural weight increases the loading on the debris slope increasing the destabilizing forces and can trigger failure.
Ir	Irrigation	Rapidly Increases groundwater recharge to the debris slope resulting in reduced effective stress. Thrust forces bring the debris slope closer to failure in the form of a debris landslide.
WLU	Water leakage from utilities	Rapidly Increases groundwater recharge to the debris slope resulting in reduced effective stress. Thrust forces bring the debris slope closer to failure in the form of a debris landslide.

Trigger Causal factors – debris landslides		Description
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can increase groundwater recharge to the debris slope resulting in reduced effective stress. Thrust forces bring the debris slope closer to failure in the form of a debris landslide.
BDB	Beaver dam burst	A beaver dam burst upstream of the tracks due to deterioration or inadequate construction can trigger a debris flow event.

7.8 Debris Landslides- Controlling Attributes

The relevant controlling attributes for debris landslide hazard scenarios include those that affect the likelihood a debris landslide event will affect the track. These include:

- Main run-out path location relative to tracks
- Location of track on debris cone
- Frequency of events
- Magnitude of events
- Run-out distance
- Catchment area
- Energy at track level
- Debris size distribution
- Particle shapes
- Slope and channel geometry
- Channel stability(avulsion potential)
- Presence of barriers or deflection berms
- Facilities at track (bridges, flumes, catch basins)

7.9 Attributes for Debris Landslide Scenarios

Debris deposits are invariably the result of geomorphic processes of the climate, rock type and structure, and processes that combine to form the natural slope profiles traversed by the railways. Thus, to understand debris landslide landform attributes requires an understanding of the natural slope profiles. Ritter et al (2002) provides a suggested division of a slope profile into nine units based on dominant geomorphic processes. Ritter et al (2002) point out that in an actual situation, not all of these units would exist. However this model is not inconsistent with the typical natural slope profiles observed in the humid-temperate climates of southern Canada with particular application to slopes in Western Canada. Missing from the model are the anthropogenic units such as highways, railways and pipelines, as well as Quaternary glaciations and postglacial units, particularly river terraces.

Predominantly debris occurs in colluvial (C), fluvial (F) and morainal (M) landforms (Cruden and Thomson, 1987). Colluvial material from bedrock is characteristically coarse and relatively easy to identify, and occurs in talus cones or colluvial blankets in unit 5. Note that material in zone 5 tends to be transient and by nature is subject to further mass movement (flow, slide, slump, creep) (Ritter et al, 2002). Colluvial materials from unconsolidated deposits have a range of grain sizes from boulders to clay with varying amounts of water and occur primarily in units 6 and 7. Coarse-grained fluvial materials are typically channel or alluvial fan deposits and are characteristically rounded and relatively sorted and generally occur in units 7, 8 and 9. Coarse-grained morainal materials are commonly associated with remnant moraines (poorly sorted) and glacio-fluvial (sorted) deposits from the recent glaciations in North America and contain a variety of grain sizes from boulders to clay. Because of the recent glaciations, remnant morainal debris deposits occur in any of the 9 units suggested by Ritter et al (2002).

Cruden and Thomson (1987) note that, as a general rule, light tones indicate well-drained coarse soils (debris) such as exposed sand and gravel. More difficult debris contains boulder sizes, which are usually evident on photography. Debris can sometimes be distinguished from rock by its lack of structure. Debris slopes are usually the result of incising into the above materials by river degradation or meandering and are commonly associated with river terraces. Anthropogenic excavations such as railway cuts and fills such as waste dumps also form debris slopes.

7.10 Debris Landslide Hazard Scenarios Consequence Likelihood Factors

7.10.1 Track Vulnerability

The tracks tend to be particularly vulnerable to debris landslides because:

- *Falls* are commonly rapid to extremely rapid, have high impact forces, have particle sizes that can derail trains and require constant ditch cleaning;

- *Slides* commonly involve large volumes, are difficult to mitigate and have particle sizes that can derail trains; and
- *Flows* are usually rapid, involve large volumes, contain particle sizes that can derail trains, are charged with water, and are associated with torrential uncontrolled water flows.

A debris landslide event can result in a track failure if it ultimately blocks or impedes the track; strikes a train; deflects the track rail surface; removes support from the track structure; changes the track gauge or damages the track components. Factors specific to debris landslides suggested to affect the likelihood the track will fail given a debris landslide scenario has occurred, and affected the track, generally include:

- Particle size, volume and distribution of material blocking track,
- Relative location of track on debris cone,
- Energy of impact, and
- Water flows.

Table 7-8 suggests track vulnerability factors in the vicinity of the track structure correlated to the mode of track failure and the type of debris landslide.

Table 7-8 Suggested track vulnerability factors corresponding to the modes of track failure and debris landslide hazard event.

Modes of Track Failure	**Causative Ground Hazards**	**Track Vulnerability Factors**
Removing support from the track structure;	• Debris slides	• Presence of retaining structures or bridges • Size, gradation and compaction of subgrade material. • Shoulder width • Ballast, sub ballast quality • Presence of revetment • Track drainage
Blocking the track;	• Debris falls, slides, flows	• Ability to retain material (barrier walls, catch fences, ditch catchment, deflection berms) • Ability for material to pass over or under tracks (bridges, culverts, flumes, sheds) • Ditch catchment
Striking a train;	• Debris falls, slides, flows	• Ability to retain or deflect material (barrier walls, catch fences, ditch catchment, deflection berm) • Ability for material to pass over or under tracks (bridges, culverts, flumes, sheds) • Ditch catchment
Changing the track gauge	• Debris falls, slides, flows	• Track quality
Damaging the track components	• Debris falls, slides, flows	• Continuous welded vs. jointed rail • Concrete vs timber ties
Damaging track structures (such as bridges, retaining walls or sheds)	• Debris falls, slides, flows	• Location, shape, orientation, and foundation type of bridge piers and abutments. • Type of retaining wall (Tie-back, cantilever, gravity) • Location, shape, orientation, capacity, abrasion protection and foundation type of rock or snow sheds.

7.10.2 Service Disruption Vulnerability

The suggested service disruption vulnerability factors for debris landslide scenarios, given that track failure has occurred, include presence or absence of warning devices such slide detector fences or tip over posts, train speed, sight lines, grades, presence or absence of central traffic control circuit in the tracks and traffic frequency. More details on these factors is given in Section 4.6.2.

7.10.3 Derailment Vulnerability

The suggested derailment vulnerability factors for debris landslide scenarios, given that track failure has occurred include presence or absence of warning devices such slide detector fences, train speed, sight lines, grades, presence or absence of central traffic control circuit in the tracks, and traffic frequency. More details on these factors are given in Section 4.6.3.

7.11 Summary

From Chapter 3, accidents attributable to debris landslides, predominantly channelized debris flow scenarios, occurred at an average frequency of 1.2 per year, severity of $170,000 direct costs per accident accounting for $200,000 per annum occurring mainly on the CN Edmonton to Vancouver near Mt.Robson, B.C. and Yale B.C. The chapter characterizes the identified debris landslide hazard scenarios from the CN Western Canada ground hazard database that contributed to these loss records.

70% of the debris landslide hazard sites are classified as complex Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow scenarios and the remaining 30% split between simple Debris Fall or Debris Slide scenarios or complex Debris Flow - Avulsion - Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow scenarios.

The Debris Flow - Avulsion – Debris Flow / Gully Erosion / Seepage Erosion / Earth Slide - Earth Flow hazard scenarios initiate with a channelized debris flow which may cause track failure by blocking the track or striking a train or a track support. Very often, the debris flow avulses with the ensuing water torrent causing a third order debris flow, gully erosion, seepage erosion and/or earth slide–earth flow events resulting in track failure by removing support or deflecting the track.

Debris fall hazard scenarios involve debris falling from above the tracks, dislodged by slope wash, gully erosion, seepage erosion, thawing or wind, resulting in track failure by blockage, striking a train or damaging track components.

Debris Slide - Seepage Erosion / Gully Erosion - Debris Fall hazard scenarios involve relatively large, slow or intermittent moving debris slides above the track, at the toe of a debris flow cone, resulting in track failure from blockage or track deflection. 2nd and 3rd order hazards involve seepage and/or gully erosion on the upper slope which erodes the fine grained matrix, dislodging larger debris particles, causing a debris falls, resulting in track failure by blockage, striking a train or damaging track components.

Debris slide scenarios identified involve a simple debris slide from above the track on shallow sloping bedrock surfaces resulting in track failure by blockage, striking a train or damaging track components.

Debris soil contains 20 to 80 percent of particles larger than 2 mm and the movement types are falls, slides and flows. Debris falls involve one of more debris particles detaching from a debris slope that fall, bounce or roll to the track. Detachment results from weathering and erosional processes undermining larger particles or changes to the slope geometry that either locally or globally over-steepens the slope. Movements are very rapid to extremely rapid, and may be preceded by minor movements.

Debris slides have a rotational, translational or compound rupture surface, controlled by the weaker matrix soil, elevated pore pressures, weak layers, sloping bedrock, bedding, or discontinuities.

A debris flow is a landslide that occurs in debris resembling the movements of a viscous fluid. There is a gradation from slides to debris flows in both debris and rock depending on water content, mobility and evolution of the movement. Debris flows are generally of two types, namely open slope or channelized debris flows. Key hazard characteristics of channelized debris flows include their mobility and the length and spatial fluctuation of their flow paths. The nature of channelized debris flows in Western Canada is described.

Observed rates of debris fall events range from rapid to very rapid and debris slide and flow events range from moderate to rapid.

Timing of debris landslides is dependent on intense rain, antecedent rain and heavy snow melt trigger causal factors. Time lags between the complex debris landslide scenarios range from minutes to months. Slow debris slides move in mid to late spring, weeks or months following snow melt, and the second order debris falls coincide with thawing of ground frost in early spring. Channelized debris flows often occur in multiples separated by minutes or hours.

Most channelized debris flow scenario sites are inaccessible, impractical to mitigate and have relatively limitless source areas, resulting in a (3) Stable – monitoring required track stability state or lower. The constant presence of preparatory causal processes for debris fall scenarios keep them in the (3) Stable – monitoring required track stability state or lower.

Observed preparatory causal factors for DFw- Av - GE / SE / ESI - EFw scenarios are stream shifts and bridge erosion and for DSI - SE / GE - DF hazard scenarios are slope wash, seepage erosion and thawing ground frost.

Suggested preparatory causal factors for debris landslides include:

Ground Conditions:

- Quaternary Glaciation
- Contrast in permeability
- Contrast in stiffness

Geomorphological Processes

- Active rock fall source
- Active avalanche source
- Glacial
- Fluvial erosion of slope toe
- Wave erosion of slope toe
- Subterranean erosion
- Vegetation removal

Physical Processes

- Low level Intense snow melt
- High level intense snow melt
- Significant antecedent rainfall
- Intense rainfall
- High groundwater recharge
- Earthquake
- Volcanic eruption
- Thawing
- Frost wedging
- Freeze-and-thaw weathering
- Wet and drying weathering
- Shrink and swell weathering
- Chemical weathering
- Wind erosion
- Vegetation

Man-made or animal processes

- Over steepening
- Shoulder over loading
- Vegetation removal
- Irrigation
- Water leakage from utilities
- Blocked drainage
- Beaver activity

The predominant observed trigger causal factors in all categories include intense rain, significant antecedent rain, snow melt and rain on snow. Additional observed trigger causal factors for debris flow scenarios is raising freezing levels and for debris fall and slide scenarios are an elevated phreatic surface, raising freezing levels, freeze and thaw and frost thaw.

The most common observed trigger causal factors for rapid channelized debris flows include intense rain, rapid snow melt and rain on snow. Debris flows are more likely when two or more trigger causal factors act simultaneously such as rain on snow with a rapid rise in the freezing level.

Suggested trigger causal factors for debris landslides include:

Geomorphological Processes

- Fluvial erosion of slope toe
- Wave erosion of slope toe
- Subterranean erosion

Man-made or animal processes

- Excavation of debris slope at its toe
- Loading of slope on its crest
- Irrigation
- Water leakage from utilities
- Blocked drainage
- Beaver dam burst

Physical Processes

- Low level Intense snow melt
- Intense rainfall
- Significant antecedent rainfall
- Seepage erosion
- Earthquake
- Volcanic eruption
- Thawing
- Freezing
- Frost wedging
- Freeze and thaw
- Heavy snow fall
- Vegetation
- Wind Throw
- Water pressure in discontinuities

The relevant controlling attributes for debris landslide hazard scenarios include run-out paths; location of track; frequency and magnitude of events; catchment area; energy at track; particle size and shape distribution; slope and channel geometry; channel stability, presence of barriers or deflection berms and facilities at track.

A natural debris slope profile divided into nine units (after Ritter et al, 2002) based on the climate, rock type and structure, durations and processes is suggested for the identification of debris land forms in Western Canada. The model is missing anthropogenic units as well as glacial and postglacial units. Predominantly debris occurs in colluvial (C), fluvial (F) and morainal (M) landforms. On monochromatic air photos light tones indicate well-drained coarse soils sand and gravel (debris) and boulder sizes are usually evident. Debris is also distinguishable from rock by lack of structure and is associated with cuts in river terraces and anthropogenic excavations.

Tracks are particularly vulnerable to debris landslide events due to the characteristics of their occurrence. Track vulnerability factors specific to the debris landslide event include particle size, volume and distribution of material blocking track; relative location of track on debris cone, impact energy, and water flows. Track vulnerability factors in the vicinity of the track structure are correlated to the mode of track failure and the type of debris landslide. The track specific vulnerability factors suggested include subgrade quality; ballast and sub-ballast quality; shoulder width; revetment; track drainage; debris catchments; retaining structures, bridge arrangement and track type and quality; and location, shape, orientation, capacity, abrasion protection and foundation type of debris, rock or snow sheds.

Suggested service disruption vulnerability factors for debris landslide scenarios include warning devices, train speed, sight lines, grades, presence of central traffic control and traffic frequency.

Suggested derailment vulnerability factors for debris landslide scenarios include presence of warning devices, train speed, sight lines, grades, presence of central traffic control and traffic frequency.

Chapter 8 Characterization of Railway Earth Landslide Hazard Scenarios: CN Western Canada

8.1 Introduction

From the review of loss records presented in Chapter 3, between 1992 and 2002, train accidents attributable to earth landslides occurred at an average frequency of 3.2 per year, severity of $698,000 direct costs per accident accounting for $2,220,000 per annum. The majority of these incidents occurred on the CN Edmonton to Vancouver corridor with the most severe event being the Conrad Earth Slide-Earth Flow event near Lytton, BC in March of 1997, which resulted in two fatalities, an eleven day outage and direct costs amounting to over $10,000,000. These statistics are for scenarios where the ground hazard event that caused track failure was an earth landslide. However, this chapter deals mainly with hazard scenarios where earth landslides are the initiating events, so Table 8-1 is provided to correlate these statistics to their associated hazard scenarios. Calculated from Table 8-1, the loss statistics for earth landslide initiated hazard scenarios include a frequency of 1.91 per year, a severity of $875,000 amounting to $1,671,000 per annum.

This chapter steps through the characterization of the identified earth landslide hazard scenarios from the CN Western Canada ground hazard database that would have contributed to these loss records. Following an illustration and description of the hazard scenarios initiating with earth landslide events, the chapter characterizes earth landslide event ground conditions and processes, rates and timing of system failure and track stability states. This is followed by identification and characterization of earth landslide hazard event preparatory and trigger causal factors, both observed and suggested by the author, followed by an identification of earth landslide controlling attributes. The chapter closes with a summary of the consequence likelihood factors for track failure, service disruption and derailment.

Table 8-1 Comparison of loss from railway complex ground hazard scenario events involving earth landslides to all ground hazard caused events in CN Western Canada 1992 to 2002

Ground Hazard Scenario	Frequency (events/year)	Severity (cost/event)	Annual cost	Proportion of ground hazard scenarios to total in Level III Class
Debris Landslide-Earth Landslide	0.09	$ 2,000,000	$ 181,818	8%
Earth Landslide-Earth Landslide	0.18	$ 6,500,000	$ 1,181,818	52%
Subsidence-Earth Landslide	0.09	$ 150,000	$ 13,636	1%
Overland flow-Earth Landslide	0.27	$ 681,667	$ 185,909	8%
Through flow-Earth Landslide	0.09	$ 10,000	$ 909	0%
Sub aqueous Flow-Earth Landslide	0.91	$ 220,400	$ 200,364	9%
Complex Earth Landslide total	***1.64***	***$ 1,078,278***	***$ 1,764,455***	***78%***
-Earth landslide	1.73	$ 283,134	$ 489,049	22%
All Earth Landslides total	**3.36**	**$ 669,961**	**$ 2,253,504**	**100%**

8.2 Earth Landslide Hazard Scenarios FMEA

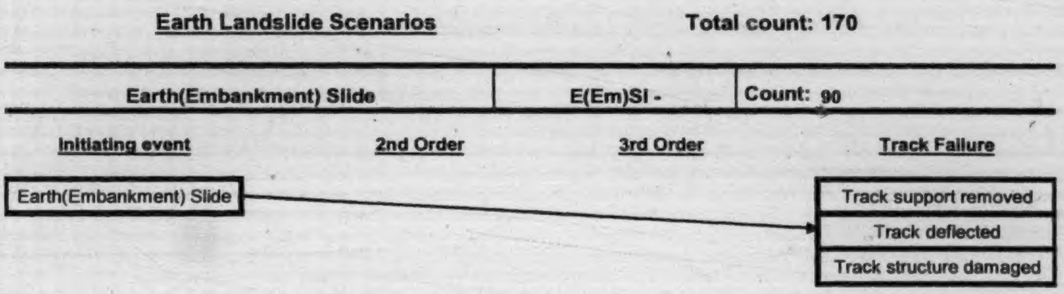
The short list of identified hazard scenarios, initiating with earth landslide events, is presented in Table 8-2. Of the six scenarios in this group, 53% are classified as simple Earth (Embankment) Slide scenarios, 38% are simple Earth Slides scenarios and the remaining 9% are evenly split between Earth Slide - Earth Flow, Earth (Embankment) Slide - Earth Flow, Earth (Embankment) Slide - Compression and Earth Slide - Earth Fall hazard scenarios. Following is an illustration and description of the FMEA for each of these scenarios.

Table 8-2 Summary of earth landslide hazard scenarios CN Western Canada

Level III Subgroups	Ground Hazard Scenario	Coding	Count
Earth Landslide Scenarios	**Earth Landslides**		
	Earth(Embankment) Slide	E(Em)Sl -	90
	Earth Slide	ESl -	65
	Earth Slide - Earth Flow	ESl - EFw -	4
	Earth (Embankment) Slide - Earth Flow	E(Em)Sl - EFw -	4
	Earth (Embankment) Slide - Compression	E(Em)Sl - Cm -	4
	Earth Slide - Earth Fall	ESl - EF -	3
	Subtotal		170

8.2.1 Earth (Embankment) Slide

Figure 8-1 depicts a simplified FMEA for the Earth (Embankment) Slide hazard scenario. As the name implies, these scenarios involve simple earth slides of railway embankments. The slide rupture surface may be contained in the embankment material or, as is usually the case, involves the weaker foundation soil. When these failures start with only minor movements, and move incrementally with train loading, the railway will tend to treat these hazards by intermittently lifting the tracks and placing ballast under the ties. This scenario can cause track failure by removing support from the track, deflecting the track, or damaging a track structure such as a retaining wall or bridge (if an approach embankment for a bridge is displaced).

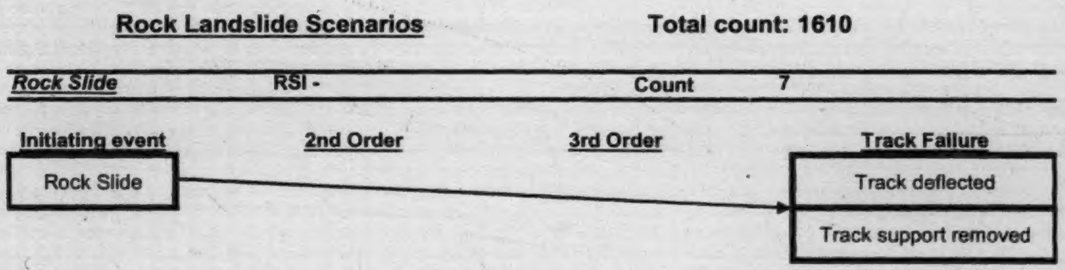

Earth Landslide Scenarios
Total count: 170
Earth(Embankment) Slide
E(Em)Sl -
Count: 90
Initiating event
2nd Order
3rd Order
Track Failure
Earth(Embankment) Slide
Track support removed
Track deflected
Track structure damaged

Notes: 1. Earth slides in embankments usually involving track from below

2. May involve foundation soil

Figure 8-1 Simplified FMEA for the Earth (Embankment) Slide hazard scenario

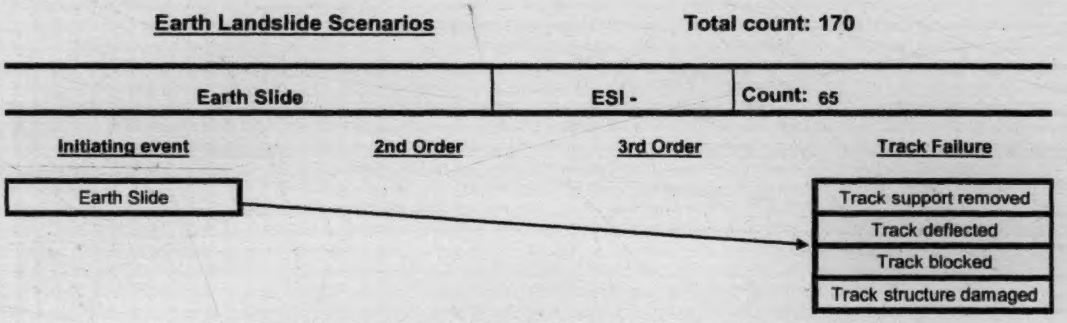
8.2.2 *Earth Slide*


Rock Landslide Scenarios
Total count: 1610
Rock Slide
RSl -
Count
7
Initiating event
2nd Order
3rd Order
Track Failure
Rock Slide
Track deflected
Track support removed

Notes: 1. Rock slides from below the tracks

Figure 6-2Figure 8-2 depicts a simplified FMEA for the Earth Slide hazard scenario. These are typically identified as existing slides that have developed in natural deposits above below or under the tracks. As depicted in

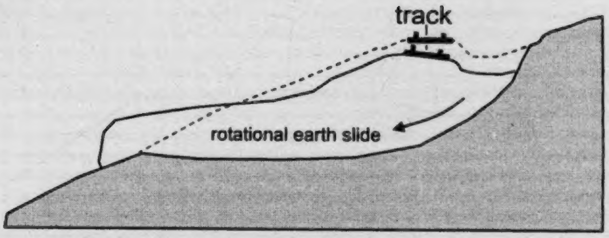
Figure **8-3**, the way in which the earth slide affects track failure depends on the relative location of the earth slide to the track. Figure 8-4 illustrates a case example where the earth slide in the lower slope in cohesive soils has resulted in track failure by deflecting and removing support from the track. The earth slide scenarios can thus cause failure by either removing track support, deflecting the track surface, blocking the track or by damaging a track structure.


Earth Landslide Scenarios
Total count: 170
Earth Slide
ESI -
Count: 65
Initiating event
2nd Order
3rd Order
Track Failure
Earth Slide
Track support removed
Track deflected
Track blocked
Track structure damaged

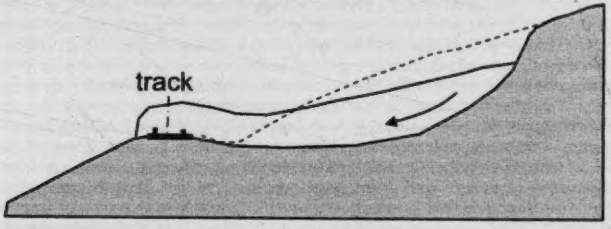
Notes:

1. Primarily cohesive earth slides affecting track either from above or below
2. Rotational, translational or compound

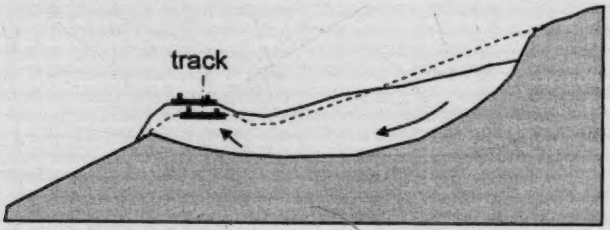
Figure 8-2 Simplified FMEA for the Earth Slide hazard scenario.


track
rotational earth slide

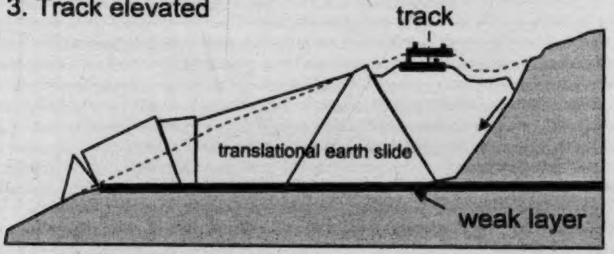
1. Track moves down slope and back tilts



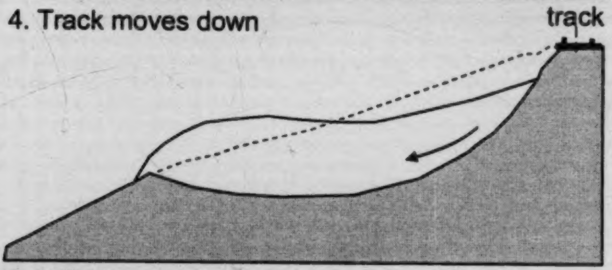
2. Track buried



3. Track elevated


track
translational earth slide
weak layer

4. Track moves down



5. Ballast support removed

Figure 8-3 The typical effects Earth Slides have on the track grade, depend on the location of the earth slide.

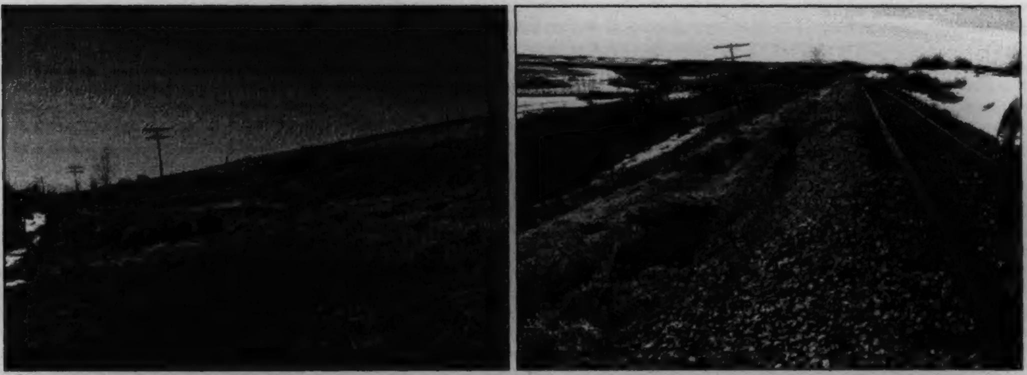


Figure 8-4 Typical Earth Slide hazard scenario @ Mile 13.4 of CN's Westlock Subdivision where an earth slide has caused track failure (track deflected and track support removed) from the lower slope. (Photos taken by Tim Keegan March 10, 2005, 11:45:00 AM, CN file: 4670-WLK- 13.4).

8.2.3 ***Earth Slide – Earth Flow***

Figure 8-5 depicts a simplified FMEA for the Earth Slide – Earth Flow hazard scenario. The four records having this hazard scenario deal with upper slope earth slides in silty material. Because of saturation, the slide mass quickly converts to a flow. The speeds and mobility of the flows depend on the length and gradient of the run out path to the tracks. A typical example of these hazard scenarios illustrated in Figure 8-6 is from Mile 92 to 95 of the CN Yale Subdivision near Abbottsford, BC. On September 5, 2004, approximately seven of these events occurred simultaneously, following 150 mm of antecedent rain over a 72 hour period. In November of 2004, an earth slide – earth flow occurred at Mile 93.3 Yale, hitting the side of an auto carrier rail car in an eastbound train, causing a major derailment at the site (BGC, 2004). This attests to the speed and mobility these flows can have. As depicted in

Figure **8-3**, the way in which the Earth Slide – Earth Flow hazard scenario affects track failure is also dependent on the relative location of the earth slide – earth flow to the track. The earth slide scenarios can thus cause failure by deflecting the track surface (Case 1, 2 or 4), blocking the track (Case 3), striking a train (Case 3), or removing track support (Case 5).

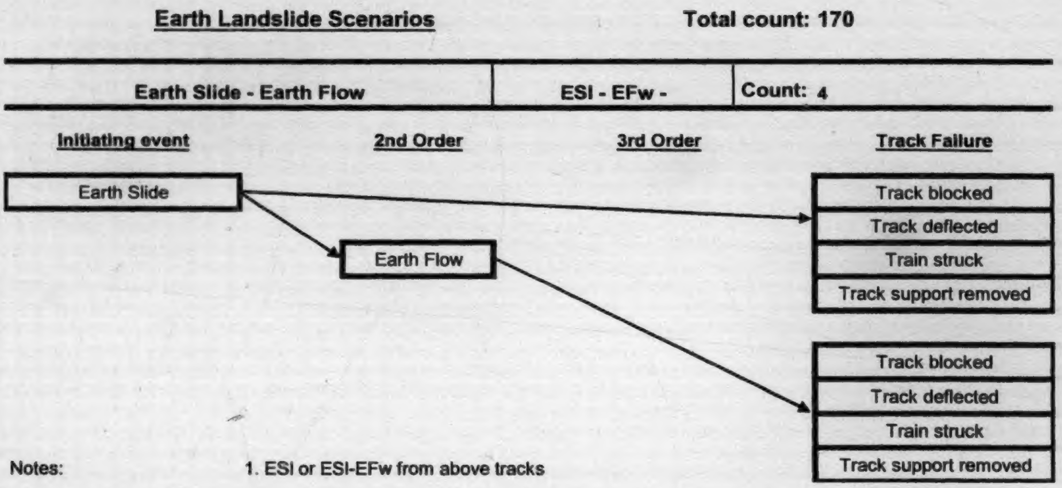

Earth Landslide Scenarios
Total count: 170
Earth Slide - Earth Flow
ESI - EFw -
Count: 4
Initiating event
2nd Order
3rd Order
Track Failure
Earth Slide
Earth Flow
Track blocked
Track deflected
Train struck
Track support removed
Track blocked
Track deflected
Train struck
Track support removed
Notes:
1. ESI or ESI-EFw from above tracks

Figure 8-5 Simplified FMEA for the Earth Slide – Earth Flow hazard scenario

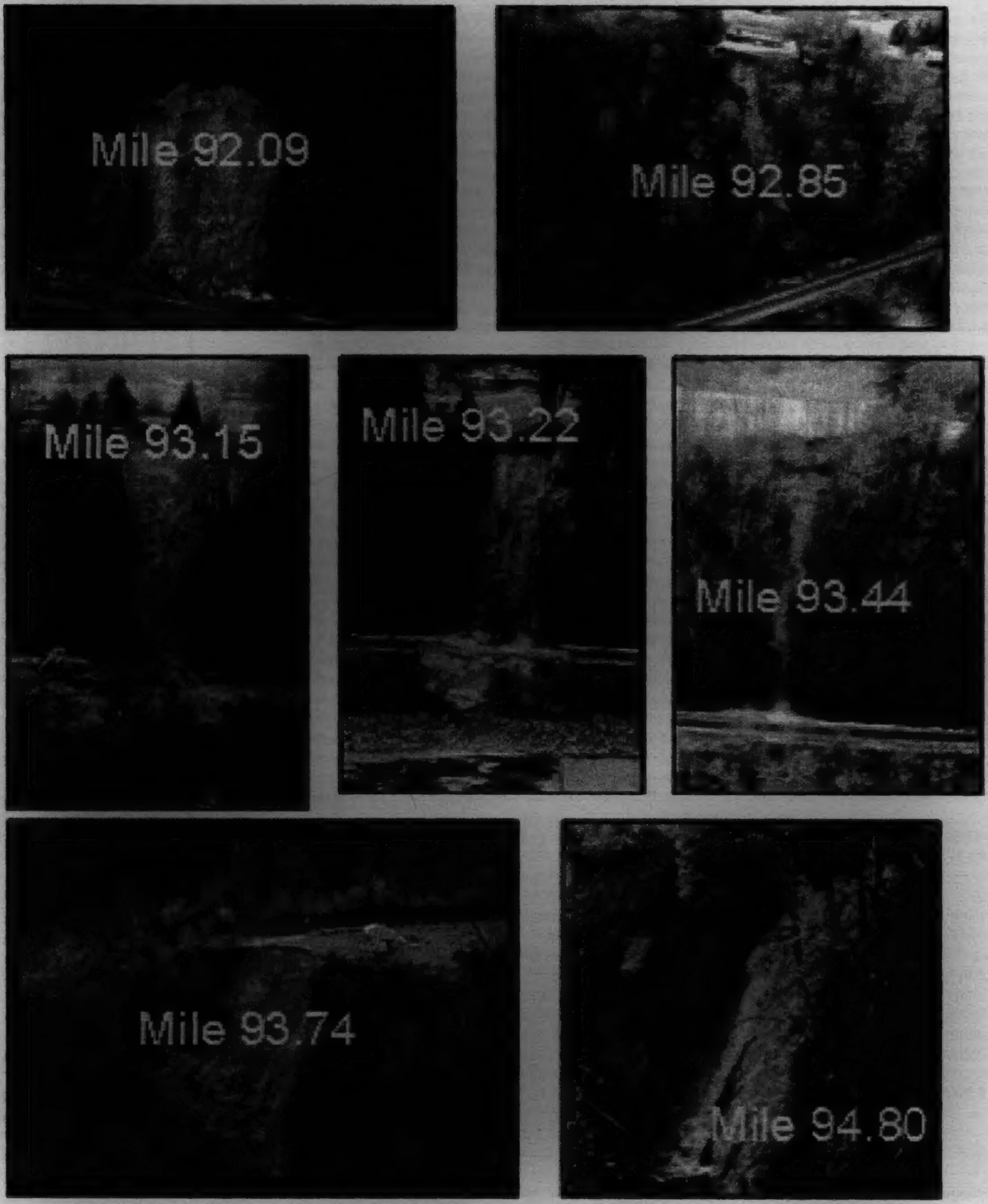

Mile 92.09
Mile 92.85
Mile 93.15
Mile 93.22
Mile 93.44
Mile 93.74
Mile 94.80

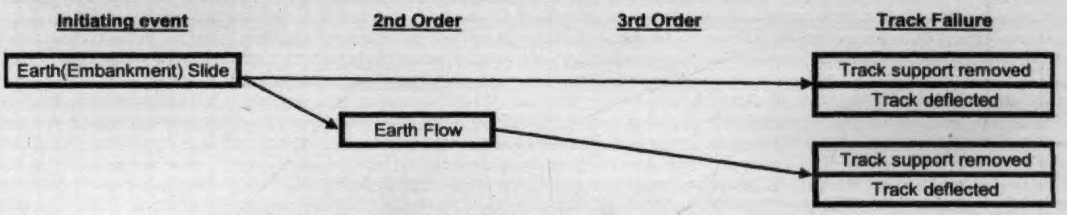
Figure 8-6 Typical Earth Slide- Earth Flow hazard scenarios @ Mile 92 to 95 of CN's Yale Subdivision where simultaneous Earth Slide-Earth Flows from the upper slope caused track failure (track blocked). (Photos taken by Tim Keegan Sunday, September 05, 2004, CN file: 4670-YLE- 92-95, (BGC, 2004)).

8.2.4 Earth (Embankment) Slide – Earth Flow

Figure 8-7 depicts a simplified FMEA for an Earth (Embankment) Slide – Earth Flow hazard scenario. Further description of the ground conditions and processes involved in these scenarios is provided in Section 8.3.4 but basically these scenarios involve rapid influxes of water into the track is non-cohesive embankments from either overland flows or through flows. The rapid rise in the phreatic surface, corresponding steep hydraulic gradient in the lower slope and, on occasion, dynamic train loading causes an earth slide to initiate. The saturated non-cohesive slide mass rapidly converts to a flow. The speed and mobility of the flows depends on the length and gradient of the run out path. An extreme example of these hazard scenarios is the fatal derailment illustrated in Figure 8-8 which occurred at Mile 106.14 at the west end of the Conrad siding on the CN Ashcroft Subdivision near Lytton, BC on March 26, 1997 (Savigny, 1997). The Conrad Earth (Embankment) Slide – Earth Flow hazard event occurred in saturated loose SM material and illustrates the very rapid movement and high mobility these scenarios can exhibit. The event was preceded by a rapid through flow influx of water from the contiguous highway embankment fill from above. Water was recharging into the highway embankment fill from an intense snow melt event which occurred one to two weeks prior to the event. These hazard scenarios are particularly difficult to identify as they show little to no sign of distress until the triggering causal factors occur. This is why there are so few of these hazards identified in the data base. They are, however, one of the most severe hazard scenarios averaging $6,500,000 per incident between 1992 and 2002 on CN Western Canada (see Table 8-1). The Earth (Embankment) Slide – Earth Flow hazard scenarios can cause failure by either removing track support or deflecting the track surface.

Earth Landslide Scenarios **Total count: 170**

Earth (Embankment) Slide - Earth Flow	E(Em)Sl - EFw -	Count: 4


Initiating event
2nd Order
3rd Order
Track Failure
Earth(Embankment) Slide
Earth Flow
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. Conrad -like embankment failures
2. High phreatic surface in non-cohesive silty soil results in earth slide
3. Saturated non-cohesive earth slide material looses cohesion and converts to earth flow.
4. Occur rapidly with little warning and can occur under train loading

Figure 8-7 Simplified FMEA for an Earth (Embankment) Slide – Earth Flow hazard scenario.

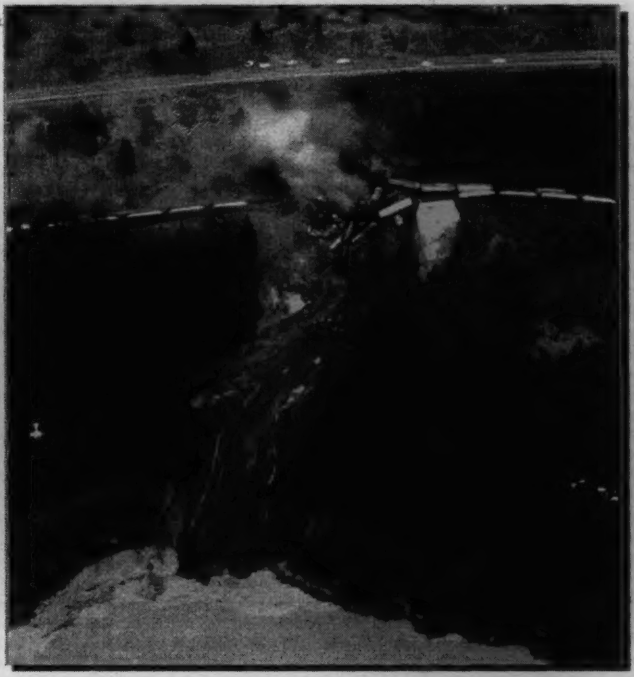


Figure 8-8 Conrad Earth Slide-Earth Flow which occurred on March 26, 1997 at Mile 106.14 of CN Ashcroft Subdivision (photo by Tim Keegan, CN file 4670-ASH-106.14)

8.2.5 *Earth (Embankment) Slide - Compression*

Figure 8-9 depicts a simplified FMEA for an Earth (Embankment) Slide – Compression hazard scenario. These scenarios involve a pre-existing earth (embankment) slide that, moved slowly, or incrementally caused the track to be lifted, inserting ballast under the ties frequently to maintain track surface. The end result, illustrated in Figure 8-10, is an overly thick section of ballast, usually on one side of the track. The thick section of ballast is essentially in a loose state, lacking lateral resistance and subject to compression settlement during train loading. The resulting track failure is associated with removal of support from the track or the track being deflected.

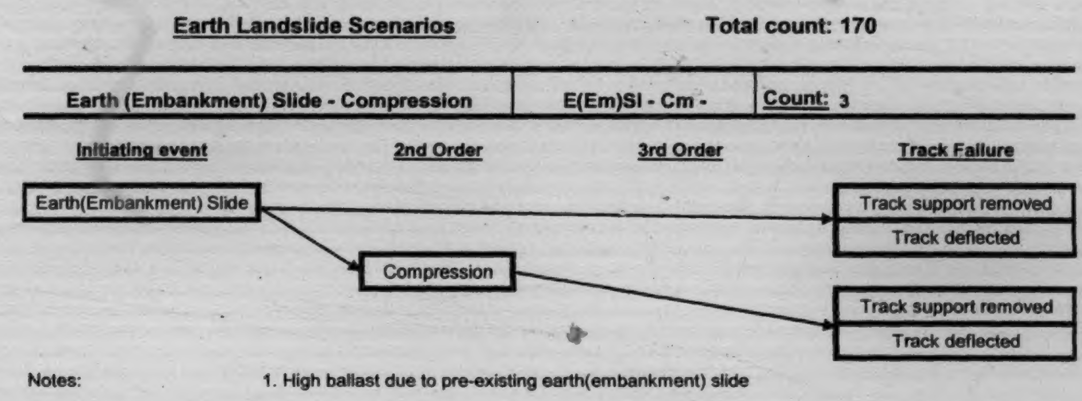

Earth Landslide Scenarios
Total count: 170
Earth (Embankment) Slide - Compression
E(Em)Sl - Cm -
Count: 3
Initiating event
2nd Order
3rd Order
Track Failure
Earth(Embankment) Slide
Compression
Track support removed
Track deflected
Track support removed
Track deflected
Notes:
1. High ballast due to pre-existing earth(embankment) slide

Figure 8-9 Simplified FMEA for the rock slide hazard scenario

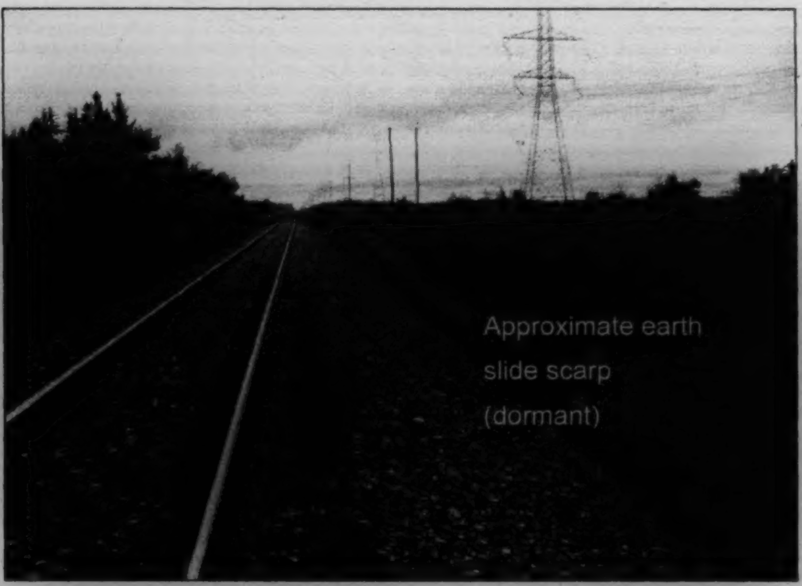
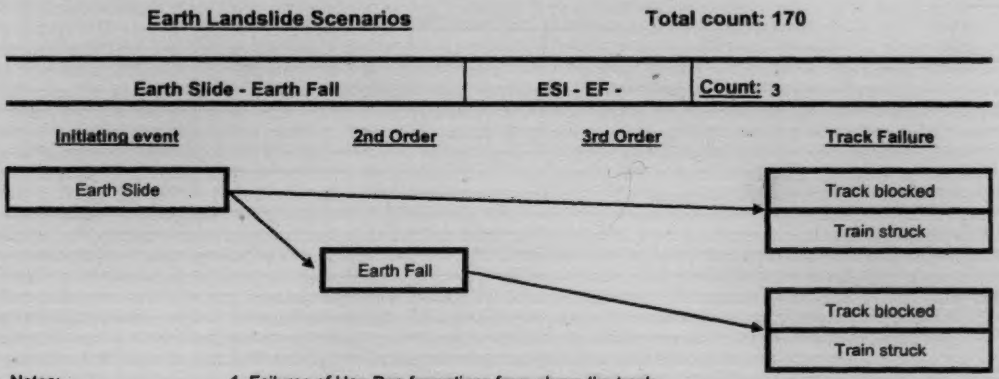

Approximate earth
slide scarp
(dormant)

Figure 8-10 Case example of an Earth (Embankment) Slide – Compression hazard scenario at Mile 122.7 of CN Vegreville Subdivision (photos by Tim Keegan, CN file 4670-VGR-122.7)

8.2.6 Earth Slide - Earth Fall

Figure 8-11 depicts a simplified FMEA for the Earth Slide – Earth Fall hazard scenario. The Earth Slide – Earth Fall hazard scenarios identified typically initiate from above the tracks with a slide of a more or less coherent block of earth that, once detached from its source area, falls, bounces or rolls fragmenting along its trajectory.


Earth Landslide Scenarios
Total count: 170
Earth Slide - Earth Fall
ESI - EF -
Count: 3
Initiating event
2nd Order
3rd Order
Track Failure
Earth Slide
Earth Fall
Track blocked
Train struck
Track blocked
Train struck

Notes:
1. Failures of Hoo Doo formations from above the track.
2. Lightly cemented silty material looses cohesion as it falls

Figure 8-11 Simplified FMEA for the Earth Slide – Earth Fall hazard scenario

An example of this hazard scenario is given by the very rapid, dry earth slide-earth fall event investigated by the author that occurred at Mile 47.4 of the CN Ashcroft Subdivision on November 18, 2006, illustrated in Figure 8-12. In this event, a large block of lightly-cemented, silty till detached from a near vertical earth slope. The slide mass fragmented as it fell along its 45° slope trajectory towards the tracks, until the majority of the slide mass had reduced to earth sizes where it accumulated at track level. This earth slide - earth fall resulted in a derailment; the two locomotives and one empty coal car essentially floated onto the earth material on the tracks. The Earth Slide – Earth Fall hazard scenario can cause track failure by either blocking the track or striking a train.

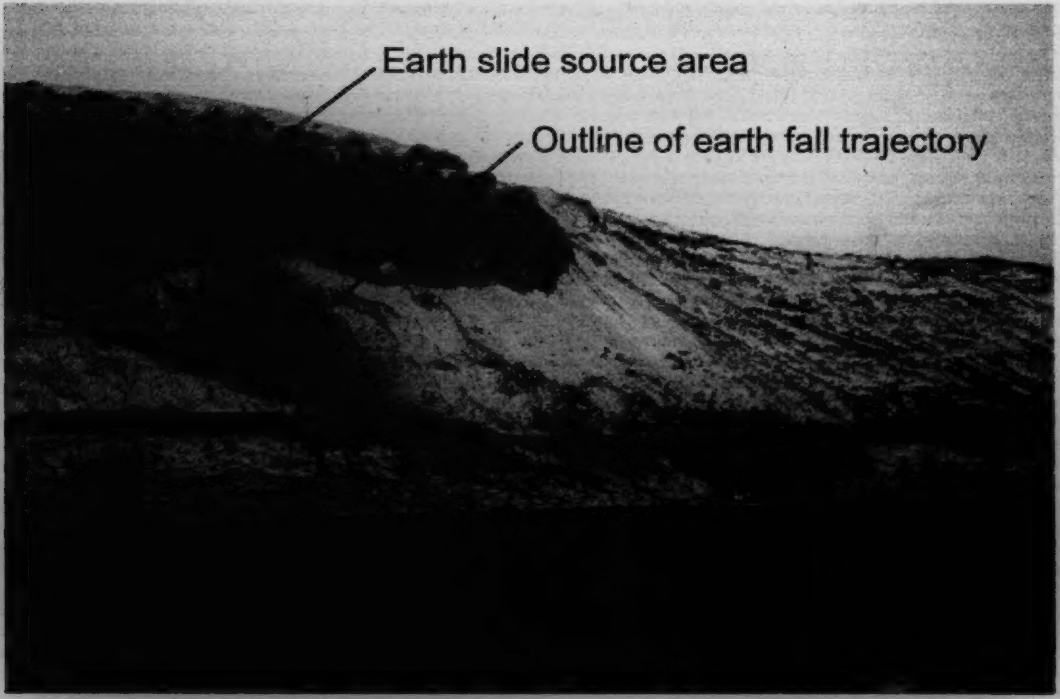


Figure 8-12 Very rapid dry earth slide-earth fall event at Mile 47.4 of CN Ashcroft Subdivision (photo by Tim Keegan, CN file 4670-ASH-47.4)

8.3 Earth Landslide Hazard Events Ground Conditions and Processes

This section describes the ground conditions and processes common to earth landslide hazard events. The soil-earth material type refers to soil, in which 80 percent or more of the particles are smaller than 2 mm, the upper limit of sand-size particles (Cruden and Varnes, 1996). The materials in this category include sands, silts, clays and highly organic soils having the Unified Soil Classification (Lambe and Whitman, 1969) group symbols SW, SP, SM, SC, ML, CL, OL, MH, CH, OH, and Pt. For the purpose of the classification system, highly organic soils (Pt) refer to earth that contains a significant proportion of organic material; greater than 20 percent by volume. Just as there is a diversity of engineering properties associated with these soil groups, there exists a diversity of failure characteristics associated with the landslides that involve them. It is therefore important in characterizing earth landslide hazards to associate the movement characteristics with the particular soil earth group and its properties.

The following sections describe the ground condition and process types for earth falls, earth slides, earth flows, earth slide –earth flows and earth spreads.

8.3.1 Earth Falls

An earth fall, starts with the detachment of earth from a steep slope or cliff along a surface on which little or no shear displacement takes place, and descends by free fall, bouncing or rolling (Cruden and Varnes, 1996). Similar to rock falls, observations show that *free fall* generally occurs when the slope below the earth fall source exceeds 76°, *bouncing* occurs on slopes at less than this angle and *rolling* occurs on slopes with angles less than 45° (Cruden and Varnes, 1996). Movements are very rapid to extremely rapid, and may or may not be preceded by minor movements. An earth fall event may involve the displacement of a single particle or many and can start as a lightly cemented mass which subsequently fragments during the fall.

Simple, very rapid earth falls are a specific class of earth fall, commonly referred to as *ravelling,* which occurs in an incremental, progressive fashion. The process starts with the removal of finer, more easily eroded soil particles by wind, train vibration, slope wash, gully or seepage erosion leaving a coarse grained rough surface. Coarse grains then begin to dislodge triggered by rainfall, wind or train vibrations. Left unchecked ravelling can retrogress and undermine and weaken the track subgrade or over-steepen the toe of a slope. As well ravelling can be a significant safety risk to personnel on or about the track, in locomotives or in passenger trains.

8.3.2 Earth slides

An earth slide is a down slope movement of an earth mass occurring dominantly on a surface of rupture or on a relatively thin zone of intense shear strain (Cruden and Varnes, 1996). The main modes of earth sliding are rotational or translational. When the sliding mass exhibits both rotational and translational movements along the basal rupture surface the movement is classified as compound. Due to the large diversity of physical properties associated with earth materials, the movement rates of earth slides range from extremely slow to very rapid.

Rotational earth slides

Rotational slides move along a surface that is curved or concave. Kinematics dictates that with this type of movement there is little internal deformation. The head of the displaced mass moves almost vertically downward and the upper surface tilts backward. The toe area of the slide bulges out from the slope or upwards if the toe of the surface of rupture extends beyond the toe of the slope. The depth (D) of the surface of rupture to length (L) of the surface of rupture ratio, D/L, for rotational earth slides range from 0.15 to 0.33 (see Cruden and Varnes, 1996). Rotational movements have the notable ability to restore the displaced mass to equilibrium. Movements can only be reactivated if the equilibrium is disturbed by loading at the head, unloading at the toe or a reduction in shear strength along the rupture surface. Because rotational slides occur most frequently in homogeneous material, they are common in embankment fills.

A common type of railway rotational earth slide, localized to the track sub-grade, is referred to by Selig (1994) as a massive shear failure and is also referred to as bearing failure. For Cruden and Varnes (1996), these are rotational earth slides. These failures occur commonly within cohesive embankment material in low embankments at locations that combine narrow shoulders, steep side slopes and weakened sub-grades. These failures occur incrementally, in response to overloading of the grade by the applied loads of trains. Weakened sub-grades commonly occur in the spring, particularly in areas where frost heaves have occurred during the winter months or as the result of significant wetting from significant antecedent rainfall.

Translational earth slides

In translational slides the earth mass displaces along a planar or undulating surface of rupture, sliding out over the original ground surface (Cruden and Varnes 1996). Translational earth slides are generally shallower than rotational slides with ratios of D/L typically less than 0.1 (Skempton and Hutchinson 1969). As natural earth deposits are seldom uniform, earth slides that occur in them tend to follow discontinuities and inhomogeneities and thus more commonly have translational movements. Discontinuities that cause translational earth slides can include shallow planar pre-existing shears but most commonly are shallow sloping bedrock surfaces. Inhomogeneities that cause translational earth slides include relatively shallow, planar, weak layers of ML, and CL to CH material.

Compound earth slides

A compound earth slide, a combination of rotational and translational movement, often indicates the presence of a weak layer at depth and such a zone often controls the location of the surface of rupture. It is inferred by kinematics that these earth slides initiate as a series of wedges with tangential rupture surfaces. The rotational shape of a portion of the rupture surface is inferred to occur only after large shear strains in the back rupture surface cutting through the stiffer material. These slides are notorious for rapid and mobile retrogressive movements associated with post glacial degradation of rivers in pre glacial buried river channel deposits. The retrogressive, compound earth slide at Mile 50.9, CN Ashcroft Subdivision (Keegan et al, 2003) is an illustration of this type of landslide.

A case example of a compound earth slide hazard scenario affecting CN trackage from below is given by the retrogressive, compound earth slide at Mile 184.03 of CN's River Subdivision near the Manitoba-Saskatchewan border (Figure 8-18), (CN File 4670-RVR- 184.03-184.1). In this example the basal translational rupture surface is through clay shale bedrock.

Outline of active slide mass
5/19/1999 4:28pm

Figure 8-13 Example of a compound earth slide at Mile 184.03 of CN's Rivers Subdivision (photo by Tim Keegan, CN File 4670-RVR-184.03-184.1).

8.3.2.1 Large Earth Slide Case Example: Ashcroft Mile 50.9

The Ashcroft Mile 50.9 Landslide is one of several large earth-slides located on both banks of the 13-kilometre reach of the Thompson River downstream of the Town of Ashcroft (Figure 8-14). Most recent studies on these earth slides were completed by Eshraghian (2007). These landslides have been troublesome to both CPR and CN since railway construction around the end of the 19th century. The nature and character of these landslides is well documented with the earliest paper by Stanton (1898) and the most recent by Porter et al (2002), Keegan et al (2003) and Eshraghian et al (2007).

The landslides formed as part of the rapid degradation of the Thompson River in post-glacial times through extensive glacial lake deposits that filled the pre-glacial valley (Holland 1976). With the thalweg still well above pre-glacial valley bottom levels over most of its length (NWH, 1977), the degradation is expected to continue. As a result, the cyclic interaction between channelized flow erosion and earth-slides is also expected to continue. The Ashcroft Mile 50.9 earth slide hazard event is part of a Local Scour /

General Scour / Channel Degradation - Earth Slide hazard scenario which is described in Chapter 11. Only the ground conditions and processes for the earth slide hazard event are presented here.

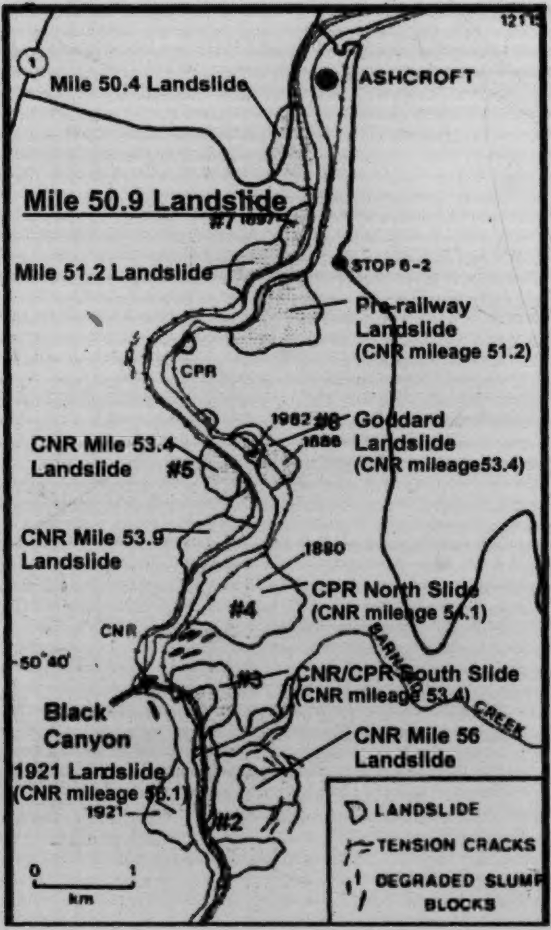

1
1211
ASHCROFT
Mile 50.4 Landslide
Mile 50.9 Landslide
#7 1897
Mile 51.2 Landslide
STOP 6-2
Pre-railway
Landslide
(CNR mileage 51.2)
CPR
1982 #6
1886
Goddard
Landslide
(CNR mileage53.4)
CNR Mile 53.4
Landslide
#5
CNR Mile 53.9
Landslide
1880
CPR North Slide
(CNR mileage 54.1)
#4
CNR
50°40'
BARNES CREEK
#3
CNR/CPR South Slide
(CNR mileage 53.4)
Black
Canyon
CNR Mile 56
Landslide
1921 Landslide
(CNR mileage 55.1)
1921
#2
0
1
km
LANDSLIDE
TENSION CRACKS
DEGRADED SLUMP
BLOCKS

Figure 8-14 Location plan of landslides south of Ashcroft B.C along CN and CPR railways. (after Keegan et al, 2003)

The Ashcroft 50.9 earth slide is a large active earth-slide situated on the right bank of the Thompson River approximately 2 kilometres south of Ashcroft in south-central BC. The CNR mainline track traverses over the active toe area of this landslide while CPR's mainline track is on the opposite riverbank.

Using Cruden and Varnes 1996) terminology the first earth-slide hazard at mile 50.9, and likely most of the others shown in Figure 8-14, was a reactivated, compound earth-slide. The concern is that the potential second earth-slide hazard is a reactivated, retrogressive, translational earth-slide. Concern arises due to the speed and mobility associated with compound earth slides that would disrupt train service and might partially or completely block the river forming a landslide dam. This is known to have occurred at other landslides within this reach such as the historic CPR North Slide that dammed the Thompson River for 44 hours in 1880 (Evans 1986). Reactivation of a compound earth-slides was also proven to be moderately disruptive by the reactivation of the Goddard Slide in September of 1982 that put the CPR out of service for 6 days.

The adjective "compound" refers to a mode of sliding intermediate between rotational and translational (Cruden and Varnes,1996). In the case at Mile 50.9, high plastic glaciolacustrine clay and silt are found at depth. Compound and translational slides often indicate the presence of a weak layer at depth and such zones often control the location of the surface of rupture.

With the translational mode of sliding there is commonly an abrupt decrease in down slope dip of the surface of rupture. Kinematically, this results in a minor, uphill dipping scarp in the displaced mass and the subsidence without rotation of the active block of displaced material that forms a graben. It is suggested that the formation of the uphill facing scarp in Figure 8-15 introduces additional driving forces that are a contributing cause of the increased speed and mobility exhibited by these earth-slides in the secondary, retrogressive translational mode of movement.

One indicator of the stage of evolution of retrogressive e[illegible]-slides is the overall slope angle measured from the crown to the tip of the landslide. Cruden et al (1993) showed that the overall slope angle for fully mature translational earth-slides on the Saddle River approximated the residual friction angle, ϕ_r', of the weak controlling surface at depth, which in that case was 8°. According to Porter et al (2002), ϕ_r' of the bedding surfaces of glaciolacustrine deposits at the Mile 50.9 Landslide, is in the range of 11° to 12 °.

Consequently slope angles for the major landslides along reachs of the Thompson River have been measured and presented on Figure 8-16. Landslides that are known to be active since the 1997 flood event are noted with an "A" in Figure 8-16. The first observation is that the landslides that have slope angles below 11°, at CNR mileages 51.2 (left bank), 54.1(left bank) and 56 (left bank), correspond to those landslides that have been observed to have undergone secondary retrogressive translational movements and are now reactivated, retrogressive, translational earth-slides. These landslides all have low slope angles, have no post-railway activity, have diverted the river which formed a meander away from them and show air-photo evidence of uphill-facing scarps. Of note also is that each of these landslides has corresponding landslides on the opposite bank of the river with slopes significantly above 11°. Landslides with slopes greater than 11°, including Mile 50.9, have sharper scarps, suggesting they are younger and may be active. At CNR mileage 53.4 the two opposing landslides appear to have balanced themselves at a slope angle of around 13.5°, still 2.5° above 11°. The most significant observation is that the Mile 50.9 Landslide has the highest slope angle at 17.5°. It is concluded from this that a secondary, retrogressive, translational earth-slide movement has yet to occur at this location. This is not to say that the secondary movement is likely in this case; there are unknown conditions such as the phreatic level, stratigraphy and bedrock surface behind the landslide that may preclude it. Nonetheless the possibility warrants significant attention.

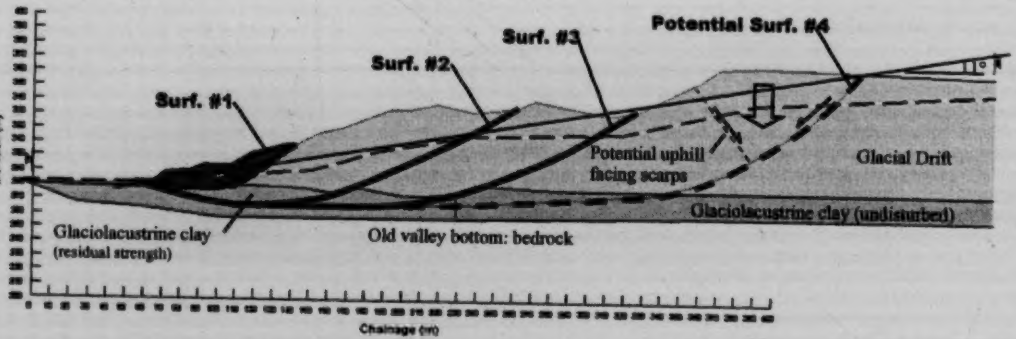

Potential Surf. #4
Surf. #3
Surf. #2
Surf. #1
11°
Potential uphill facing scarps
Glacial Drift
Glaciolacustrine clay (undisturbed)
Glaciolacustrine clay (residual strength)
Old valley bottom: bedrock
Elevation (m)
Chainage (m)

Figure 8-15 Mile 50.9 Landslide general surface stability back-analysis section (Keegan et al (2003)).

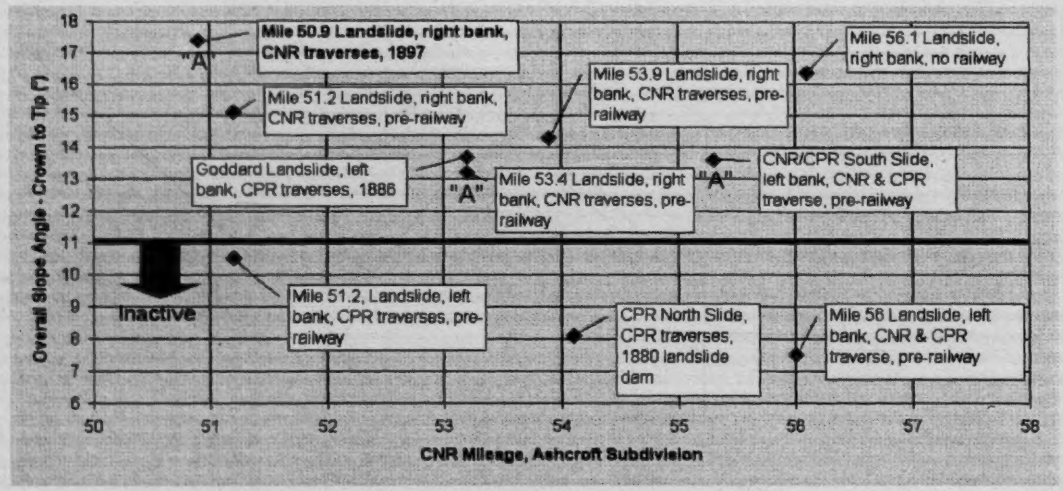


Figure 8-16 Overall slope angle of earth slides downstream of Ashcroft, B.C. on the Thompson River.

The triggering event for the reactivated, multiple rotational earth-slide, using Wieczorek's (1996) definition, is suggested by the author, and supported by Eshraghian et al (2007), to be draw-down conditions brought on by low river levels in the Fall or Winter months following flood and scour events. This is supported by a correlation between river level and slide movements highlighted in Figure 8-17 which shows movement rates measured on the rupture surface in the toe area of the Mile 50.9 Landslide plotted against river levels from April to October of 2001.

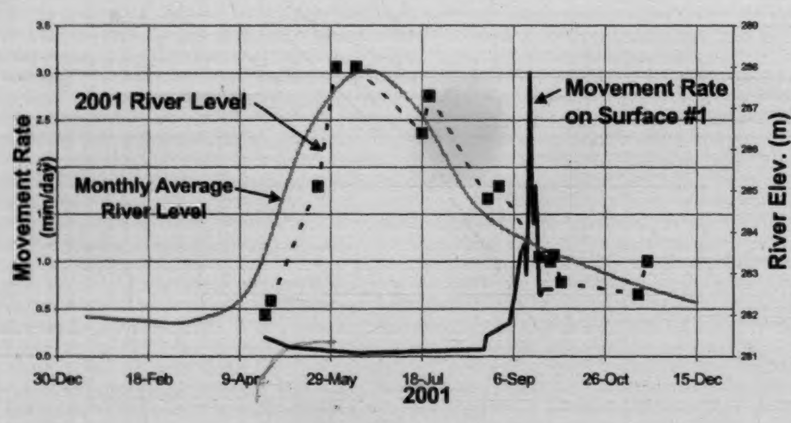


Figure 8-17 Mile 50.9 Landslide: Toe block movement rates versus river level during 2001.

A cross section of the slide is shown in Figure 8-15. Failure surfaces are interpreted from slope indicator readings and known scarps. Surface #4 is inferred from a lowest factor of safety truncated slip-circle search in Slope-W©, $45°+\phi/2$ scarp dip and an arc shaped depression observed behind the existing crown. Piezometric levels are taken from instrumentation near the toe of the slope and extrapolated back to mimic ground surface. Analysis indicates that surfaces #1 and #2 have factors of safety marginally above unity. The stability of surfaces #3 and potential surface #4 are relatively higher provided the glaciolacustrine clay remains undisturbed. When the shear strength in the glaciolacustrine clays is dropped from $\phi_P'=19°$ and $c'=20$ kPa to the residual strength of $\phi_r'=11°$ and $c'=0$ along surface #4 in the analysis there is a 19% drop in sliding resistance. This condition could be triggered were there excessive movements and stress release on surfaces #1, 2 or 3 (strain weakening). Another possible trigger for movement on surface #4 is an incremental increase in pore pressure in the glaciolacustrine deposits resulting from events such as high antecedent precipitation or up slope irrigation.

This case example illustrates the complex interaction between postglacial degradation of river systems and landslide movements as well as the controlling aspects of the weak soil layer at depth.

8.3.3 Earth flows

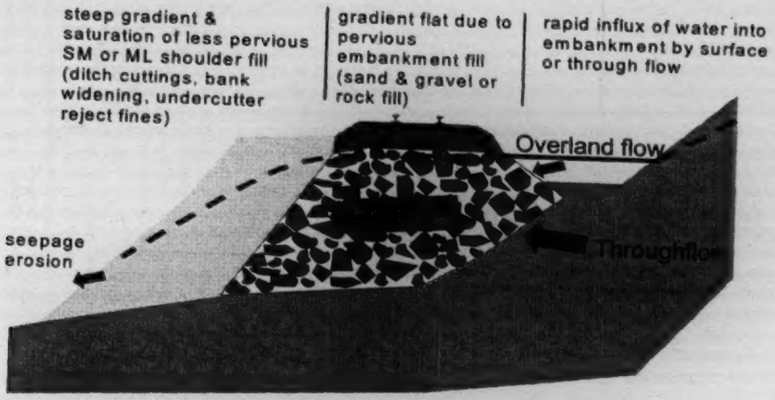
A flow is a spatially continuous movement in which shear surfaces are short lived, closely spaced, and usually not preserved (Cruden and Varnes, 1996). It resembles the movements of a viscous fluid. An earth flow is thus described as this type of movement that occurs in earth. The velocity is greatest at the surface and decreases downward in the flowing mass. Earth flow movement velocities can range from very slow to very rapid. The soil groups and properties that have the highest potential to form rapid to very rapid earth flows include saturated, loose SM and ML materials and high sensitive or quick clay materials as they each have a propensity to rapidly loose shear strength or cohesion.

8.3.4 Earth Slide-Earth Flow and Earth (Embankment) Slide-Earth Flow

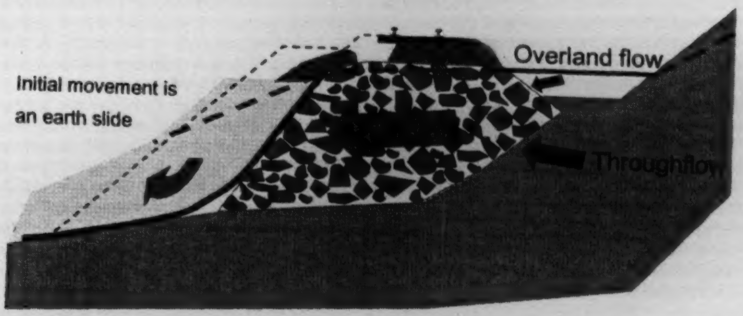
Earth slide-earth flow and earth (embankment) slide-earth flow hazard events are two of the most severe ground hazard events known to the author. All too often these events result in catastrophic failure of the railway grade such as in the Conrad earth (embankment) slide-earth flow illustrated in Figure 8-8 (CN file 4670-ASH-106.14). The common denominator with these hazard events is a high phreatic surface in a slope made up of loose or contractive, fine, non-cohesive soils.

Railway embankments are particularly prone to this type of failure primarily due to the nature of their construction and maintenance practices. Most embankments were constructed initially with relatively pervious granular material under the tracks and then, over the years, spoils from ditch cleaning or finer materials used for bank widening were dumped on the downstream slope forming a loose, less pervious slope of SM or ML material. The failure process typically starts with a rapid and sustained overland or through flow influx of water into the embankment from the upstream side. This sets up a significant differential head across the embankment. As the seepage encounters the less pervious material in the downstream slope, the phreatic surface rises quickly and a steep hydraulic gradient is set up within the downstream slope. The resulting landslide typically starts as an earth slide but the slide mass quickly loses cohesion converting to an earth flow.

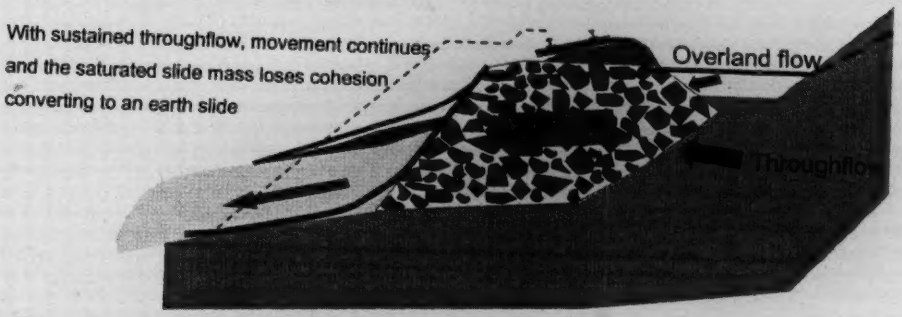
Figure 8-18 (a), (b) and (c) illustrates the author's interpretation of the typical sequence of events that ultimately results in track failure. Figure 8-19 illustrates one of several earth slide-earth flows that occurred between Mile 10.1 and 10.3 of the CN Robson Subdivision in July 2001 following intense rain which triggered a debris flow followed by a stream avulsion. The uncontrolled overland water from the avulsion ponded in the uphill ditch, percolated through the more pervious embankment core, backed up against the relatively impervious downstream slope which subsequently set up the conditions for earth slide-earth flows. A similar earth slide-earth flow caused the derailment seen in the background in Figure 8-19.


steep gradient & saturation of less pervious SM or ML shoulder fill (ditch cuttings, bank widening, undercutter reject fines)
gradient flat due to pervious embankment fill (sand & gravel or rock fill)
rapid influx of water into embankment by surface or through flow
Overland flow
seepage erosion
Throughflow

a) Rapid influx of water


Overland flow
Initial movement is an earth slide
Throughflow

b) Earth slide develops


With sustained throughflow, movement continues and the saturated slide mass loses cohesion converting to an earth slide
Overland flow
Throughflow

c) Subsequent movement earth flow

Figure 8-18 Sequential illustration of typical earth slide-earth flow railway embankment failures.

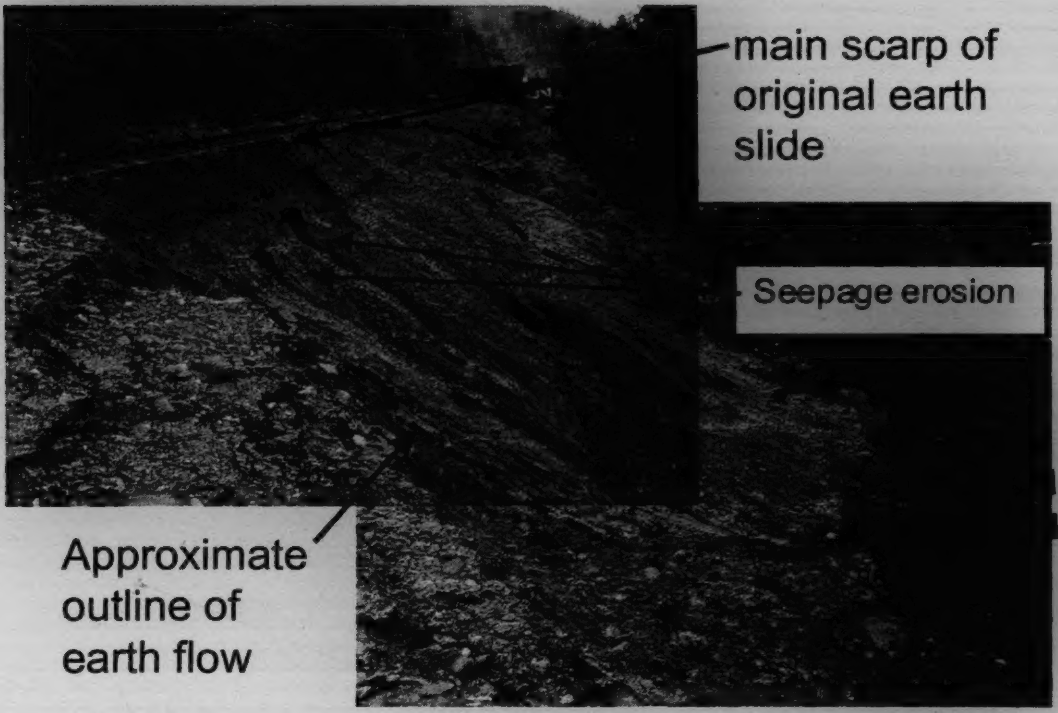

main scarp of original earth slide
Seepage erosion
Approximate outline of earth flow

Figure 8-19 Earth slide-earth flow Mile 10.2 CN Robson Sub. (photo by Tim Keegan, CN file 4670-RBS-10.1-10.3)

8.3.4.1 Earth spreads

Cruden and Varnes (1996) define an earth spread as an extension of a cohesive soil mass combined with a gentle subsidence of the fractured mass of cohesive material into softer underlying material. The surface of rupture is not a surface of intense shear. Spreads may result from liquefaction or flow (and extrusion) of the softer material. The cohesive material may also subside translate, rotate, disintegrate, or liquefy and flow. The only earth spread event identified in the CN Western Canada database is contained in the Consolidation – Earth (peat) Spread hazard scenario and involves failure of the stiffer granular embankment into the much softer peat substrata. Commonly railway embankments constructed over peat were built using a layer of corduroy. Corduroy is a common term refering to the mat of crisscrossing trees laid down ahead of construction to support the embankment on weak and compressible highly organic soils and peats. The practice is similar to the present day use of geotextiles over soft subgrades. Over time, as the organic soils consolidate the corduroy mat would provide tensile strength to the base of the embankment fill resulting in an even distribution of the overburden loads preventing shear failure into the low strength organic soils. This was successful provided the fill was placed slowly and the buried timber did not deteriorate and lose its tensile strength. It is suggested an earth (peat) spread, a rapid tearing of the decomposed corduroy, typically occurs under train loading and is followed by a rapid, , subsidence of the fractured earth embankment into the much softer peat.

Figure 8-20 illustrates two case examples of Consolidation – Earth (peat) Spread with suspected corduroy failure of earth embankment over peat at Mile 46.6 of the CN Redditt Subdivision(CN File 4670-RDT-46.6) that occurred in September 2001 and Mile 86.6 of the CN Fraser Subdivision (CN File 4670-FSR-86.6) that occurred in September 11, 2002. The main preparatory cause of the Mile 46.6 Redditt event is suspected to be the lowering of the phreatic surface on the upstream side of the embankment of about 3 metres 5 years prior to the failure with the installation of a lower culvert and removal of beaver dams. It is suspected the phreatic surface dropped below the timber corduroy mat exposing it to oxygen, which would have accelerated the rotting process in the timber reducing its tensile strength. The embankment failed under train loading after three weeks of no rain in late summer.

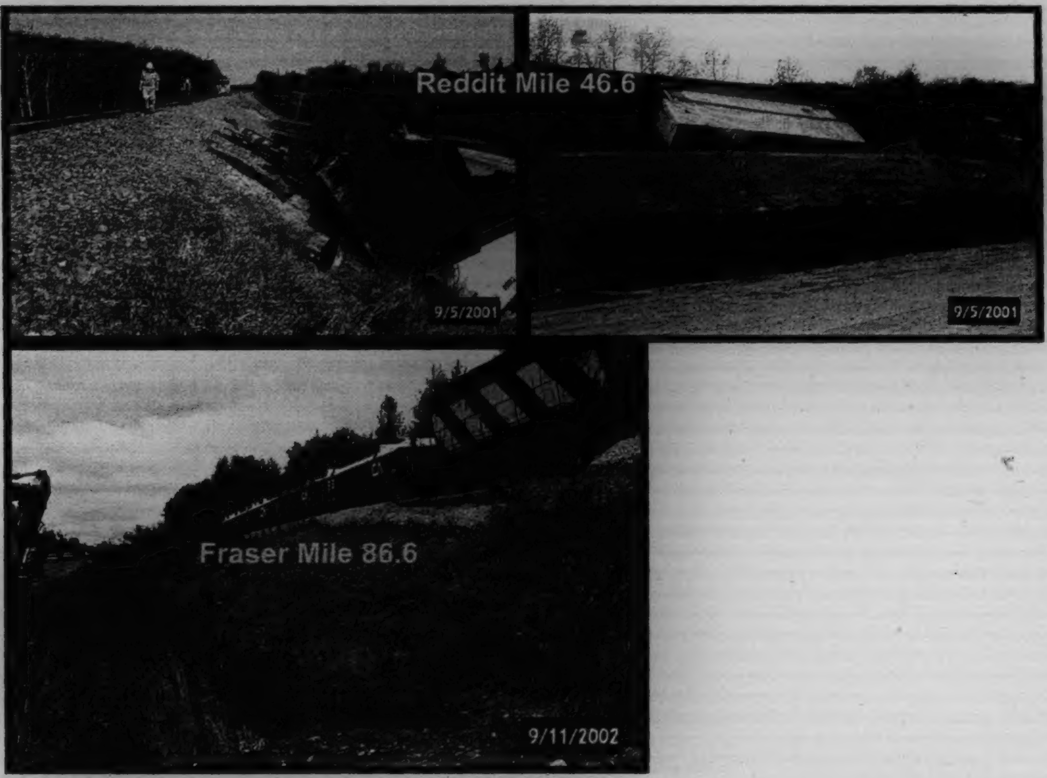


Figure 8-20 Earth (peat) Spread events and derailments at Mile 46.6 CN Redditt Subdivision (upper two photos) and Fraser Subdivision Mile 86.6 (lower photo). Suspected corduroy failures (photos by Tim Keegan, CN files 4670-RDT-46.6 and 4670-FSR-86.6).

8.4 Earth Landslide Hazard Scenarios Rates of Ground Hazard System Failure

Table 6-2 presents a summary of the subjectively estimated rates of track failure recorded by the author for the CN Western Canada earth landslide hazard scenarios. In general terms when the ultimate event in the scenario involves a slide such as the Earth (embankment) Slide or Earth Slide scenarios the estimated rates of track failure range from slow to rapid. Of relevance is that the majority of these scenarios are identified after initial movements have occurred inferring that the rupture surface has formed. From the author's experience, the ongoing *non-track-failure* movements of these earth slides tend to be very slow or incremental suggesting that cohesive soils are controlling the movements resulting in track failure. When the ultimate event involves a flow or fall, it tends to be estimated as rapid to very rapid that either saturated non-cohesive or work-softening soils are controlling the movements resulting in track failure. Formation of active blocks can also cause rapid movements as discussed in Section 8.3.2.1. Although there are quick marine clays known to exist in CN's Kitimat Subdivision in northwestern BC (Geertsema et al, 2006), there are no earth slide – earth flow hazard scenarios involving quick clays identified in the CN Western Canada ground hazard database.

Table 8-3 Rates of track failure recorded for earth landslide hazard scenarios.

				Percentage of Ground Hazards Reporting this Speed				
Level III Subgroups	**Ground Hazard Scenario**	**Coding**	**Count**	**Very Rapid**	**Rapid**	**Moderate**	**Slow**	**Very Slow**
Earth Landslides	**Earth Landslides**							
	Earth(Embankment) Slide	E(Em)Sl -	90	0%	30%	7%	20%	4%
	Earth Slide	ESl -	65	0%	22%	8%	25%	6%
	Earth Slide - Earth Flow	ESl - EFw -	4	25%	25%	0%	25%	0%
	Earth (Embankment) Slide - Earth Flow	E(Em)Sl - EFw -	4	100%	0%	0%	0%	0%
	Earth (Embankment) Slide - Compression	E(Em)Sl - Cm -	4	0%	0%	25%	50%	25%
	Earth Slide - Earth Fall	ESl - EF -	3	33%	67%	0%	0%	0%
		Subtotal	**170**	**4%**	**26%**	**7%**	**22%**	**5%**

The timing of track failure from the six earth landslide scenarios depends on the trigger causal factors for the individual ground hazard events in the scenarios and the lag time between these events. Table 9-3 provides the observed trigger causal factor controlling the timing for each ground hazard event in the earth landslide scenario and the estimated range of lag time between the ground hazard events.

Table 9-3 Observed timing and estimated time lag for earth landslide scenarios

Earth Landslide Scenario	Timing of Individual event	Lag Time Between Events
E(Em)Sl -	• Following significant antecedent rain or snow melt • Incremental with train loading	NA
ESl -	• Following significant antecedent rain or snow melt • Incremental with train loading	NA
ESl - EFw -	• Following significant antecedent or intense rain or snow melt	• Minutes to hours
E(Em)Sl - EFw -	• Following significant antecedent or intense rain or snow melt	• Minutes to hours
E(Em)Sl - Cm -	• Following significant antecedent rain or snow melt • Incremental with train loading	• Months to years
ESl - EF -	• Following significant antecedent or intense rain or snow melt • Following temperature drop to below freezing i.e."ice jacking"	• Seconds

8.5 Earth Landslide Hazard Scenarios Track Stability States.

As the majority of the identified earth slide and earth (embankment) slide scenarios are reactivations of earth slides, unless effective mitigation has been applied, these hazards generally exist in the (2) *Marginally Stable* to (3) *Stable – monitoring required* track stability states(see Section 4.4.5.3). Provided the movement rates are very slow and constant through successive cycles of seasons, ongoing railway inspection and maintenance can maintain a location in the (3) *Stable – monitoring required* track stability state for many years. However, long term incremental movements of an earth slide under a track can weaken the track support by over thickening the ballast layer creating an Earth(Em) Slide – Compression scenario or by opening up cracks in the embankment or slope which can subsequently fill with water. Mitigations such as buttress berms, shear keys and some drainage works are very often sufficient to move the earth landslide scenario into the (4) *Stable* track stability state however the site should be monitored for at least one cycle of seasons.

The track stability states for site specific Earth Slide-Earth Flows and Earth (Embankment) Slide-Earth Flow scenarios are difficult to assess simply because it is difficult to identify these ground hazards. Indirectly the track stability states can be estimated for a section of track using real time, climatic trigger, causal factors such as antecedent rain conditions. For example, if a predetermined climate criteria is exceeded for a section of track known to be susceptible to earth slides – earth flow scenarios that section of track is considered to be at the (2) *Marginally Stable* state.

8.6 Earth Landslide Hazard Scenarios Preparatory Causal Factors

8.6.1 Observed Earth Landslides Preparatory Causal Factors

Error! Reference source not found. presents the preparatory causal factors identified for each earth landslide hazard scenario. The following sections discuss the preparatory causal factors for earth landslides indicated on the geotechnical inspection form by the author for each earth landslide scenario.

8.6.1.1 Earth Slides

The most common preparatory causal factor observed for earth (embankment) slide and earth slide hazard scenarios was a depleted shoulder indicated by either shoulder sloughing or ballast raveling. The author's thought when filling in these fields was that the embankment or natural slope below the tracks was now compromised by either the initiation of an earth slide on that slope or the potential for an earth slide due to the combined factors of incremental train loading and reduced shear resistance caused by the depleted shoulder. Of relevance is the even split of non-cohesive (36%) and cohesive (39%) fine material being reported as the potential slide material.

A railway specific preparatory causal factor not included on the geotechnical inspection form is the presence of a ballast trough. Over time, train loading and periodic lifting of the track by placing additional ballast rock under the ties, forms a ballast filled trough in the subgrade which acts as a preferential path for water to flow or pond under the tracks. Where the ballast trough is locally lower, an enclosed depression in the ballast is formed and water from intense rain, significant antecedent rain or snow melt, flows along the ballast trough, and pools. This can result in a saturation zone directly below the track structure well within the stress envelope from train loading. The pooling water can infiltrate the subgrade producing a downward-moving, wetting front, decreasing the stability of the track subgrade by producing positive pore pressures in the upper portion of the slope (or embankment) or filling pre-existing cracks. Each activation or reactivation of movement enhances these conditions. It is usually only a matter of time before an earth slide becomes actively unstable and the track failure occurs. Figure 8-21 illustrates a case example of an earth slide suspected to be caused by seepage from a ballast trough at Mile 0.6 of the CN Rivers Subdivision, Winnipeg, Manitoba (CN file 4670-RVR-0.6-1.0). This location had a history of chronic settlement indicating the likely presence of a ballast trough and the earth slide initiated some time earlier in 2006.

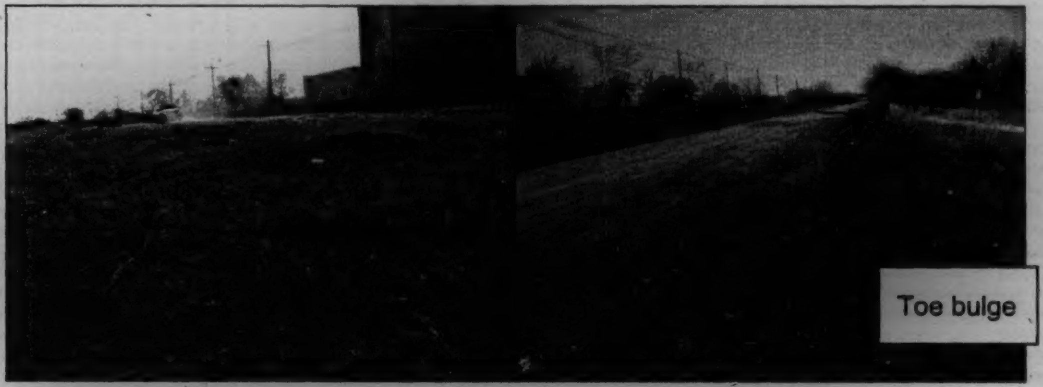


Figure 8-21 Case example of an earth slide caused by seepage from a ballast trough at Mile 0.6 of the CN Rivers Subdivision, Winnipeg, Manitoba (Photos by Tim Keegan on April 24, 2006, CN file 4670-RVR-0.6-1.0

8.6.1.2 Earth Slide – Earth Flow

The most notable preparatory causal factors reported in **Error! Reference source not found.** for Earth Slide – Earth Flow and Earth(embankment) Slide – Earth Flow scenarios are the presence of slope or seepage erosion, plugged ditches and poor culvert inlet arrangement. These preparatory causal factors are indicators that there may be an elevated phreatic surface and seepage in the subgrade below the tracks. The only ground condition preparatory causal factors reported for these scenarios are earth fines (25 to 50%) indicating non-cohesive silty soils. Assuming the soils are non-cohesive, the combination of these conditions may indicate the track subgrade within the stress envelope from train loading is now saturated and excess pore pressures can now be generated. The resulting drop in effective stress may be sufficient to cause shear failure of the track sub-grade and the supporting slope.

Figure 8-22 illustrates a case example of an Earth Slide –Earth Flow that resulted in a derailment in June 3, 1996 at Mile 151.4 CN's Edson Subdivision. In this instance the train crew reported feeling a slight dip when the lead locomotive rolled over the site. This prompted the conductor to look back on the down hill side and he witnessed the Earth Slide –Earth Flow event under approximately the fourth rail car behind the three locomotives. This event was preceded by approximately 80 mm of rain which fell in a 24 hour period, 24 hours prior to the incident. It is suggested that this rain recharged the exposed permeable sandstone bedrock in a borrow pit 100 metres upslope of the site. The recharged groundwater permeated through the fractured sandstone and recharged the three metre deep, silty colluvium soils supporting the track over the bedrock. The elevated phreatic surface, increased seepage and elevated hydraulic gradient represented preparatory causal factors that brought the slope system to a *marginal* activity stage and the track to a (2) *marginally stable* state (see Section 4.4.5.3). Train loading triggered the track failure.

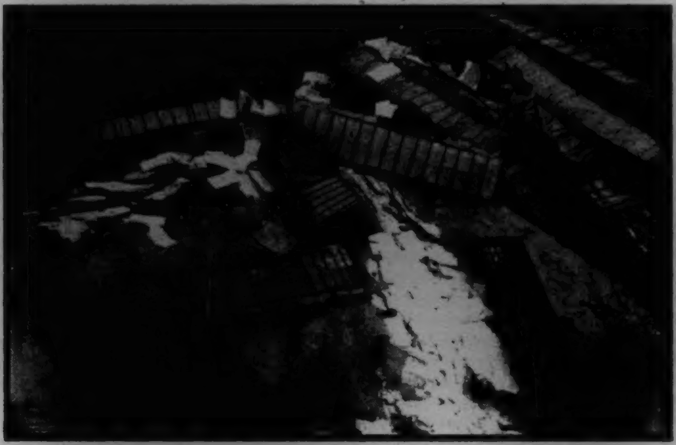


Figure 8-22 Earth Slide – Earth Flow event and 19 car derailment at Mile 151.4 CN Edson Subdivision (photo Edmonton Sun newspaper June 4, 1996, CN file 4670-EDS-151.4).

8.6.1.3 Earth (Embankment) Slide – Compression

The only preparatory causal factor reported for this scenario is evidence that the shoulder had either sloughed or dropped and ballast had sloughed.

8.6.1.4 Earth Slide – Earth Fall

Preparatory causal factors reported for this scenario include evidence of piping, slope wash or seepage erosion. As well fine grained non-cohesive soils were reported for all three of these sites.

evel III ubgroup	Ground Hazard Scenario	Coding	Count	Erosion	Poor Drainage	Beaver Activity	Landslide Material	Landslide Movement Type	Other Observations
Earth Landslides	**Earth Landslides**								
	Earth(Embankment) Slide	E(Em)Sl -	90	Slope (1%),	Partially(2%),Blocked(2%),Poor Inlet(1%),Ponding or HWT(4%),Marshes(1%),Plugged Ditches(3%),Anthro(1%).	Active(1%),Habitat(1%),	Debris(3%),Earth(100%),Earth Coarse(33%),Earth Fine(35%),Earth Cohesive(43%),	Fall(1%),Slide(90%),Spread(6%),Flow(1%),	Shoulder Sloughing(26%),Ballast Sloughing(13%),Damaged Structure(1%),
	Earth Slide	ESl -	65	Seepage (5%),	Ponding or HWT(2%),Marshes(2%),Plugged Ditches(3%),Anthro(2%).	Active(2%),Habitat(2%),	Earth(100%),Earth Coarse(20%),Earth Fine(37%),Earth Cohesive(36%),	Slide(100%),	Shoulder Sloughing(28%),Ballast Sloughing(18%),Damaged Structure(5%),
	Earth Slide - Earth Flow	ESl - EFw -	4	Slope (25%),Seepage (50%),	Plugged Ditches(25%),		Earth(100%),Earth Fine(25%),	Slide(100%),Spread(25%),Flow(100%),	
	Earth (Embankment) Slide - Earth Flow	E(Em)Sl - EFw -	4		Poor Inlet(75%),		Earth(50%),Earth Fine(50%),	Slide(50%),Flow(50%),	
	Earth (Embankment) Slide - Compression	E(Em)Sl - Cm -	4				Earth(100%),Earth Cohesive(25%),	Slide(100%),	Shoulder Sloughing(75%),Ballast Sloughing(50%),
	Earth Slide - Earth Fall	ESl - EF -	3	Piping (33%),Slope (67%),Seepage(33%),			0%),Earth Fine(100%),	Fall(67%),Topple(100%),Slide(67%),	
	Subtotal		170	Slope (2%),Seepage (4%).	Partially(1%),Blocked(1%),Poor Inlet(2%),Ponding or HWT(3%),Marshes(1%),Plugged Ditches(4%),Anthro(1%).	Active(1%),Habitat(1%),	Debris(2%),Earth(99%),Earth Coarse(20%),Earth Fine(38%),Earth Cohesive(37%),	Fall(2%),Topple(2%),Slide(96%),Spread(4%),Flow(4%),	Shoulder Sloughing(27%),Ballast Sloughing(15%),Damaged Structure(2%),

Table 8-4 Preparatory causal factors identified for each earth landslide hazard scenario grouped into erosion, poor drainage, beaver activity, landslide material, landslide movement type and other observations. The percentage each preparatory causal factor was reported for each hazard scenario is presented in brackets.

8.6.2 Suggested Earth Landslide Preparatory Causal Factors

The diversity of soil types and their complex physical characteristics, particularly in Western Canada, make earth landslides the most difficult group of railway ground hazards to manage. Because of the relative weakness of earth soils, earth landslides do not require particularly high relief terrain to occur. As well, the preparatory causal factors for earth landslides tend to be internal or less obvious than for other landslides. Consequently the proper identification and awareness of the causal factors for earth landslides is more critical than for other ground hazards. Table 8-5 presents the preliminary listing of railway earth landslide hazard preparatory causal factors and description of each.

Table 8-5 Preliminary railway earth landslide hazard preparatory causal factors.

Preparatory Causal Factors - earth landslides		**Description**
1.Ground Conditions		
QGM	Quaternary Glacial Materials	Quaternary glacial fluvial, glacial lacustrine, post glacial lacustrine or postglacial fluvial erosion resulted in. significant lacustrine and fluvial earth landforms having ground conditions that increase the likelihood of earth landslides.
CP	Contrast in permeability	Results in a build up of water pressures and seepage forces above interface reducing effective stress and shear strength and increasing thrust forces. Preferred flow paths and increased seepage forces cause internal erosion and concentrated seepage erosion from the slope.
CS	Contrast in stiffness	Boundary formed by loose or weak earth deposits over stiff, dense or cohesive materials such as bedrock or consolidated deposits introduces potential sliding surface causing an earth landslide hazard. Conversely stiff earth deposits over weak earth deposits increase the likelihood of deep seated earth landslides

Preparatory Causal Factors - earth landslides		**Description**
HWED	Homogenous weak earth deposits	Earth soils such as CH, MH, OL, CL and ML commonly found in the following landforms: lacustrine, glacio lacustrine, moraine, ditch spoils anthropogenic cuts and fills.
C	Corduroy	Presence of corduroy under a railway embankment primarily in peat areas predisposes the track to earth slide or spread failures.
2.Geomorphological Processes		
FET	Fluvial erosion of slope toe	Ongoing or periodic stream erosion of earth slopes below and above the tracks causing oversteepening
WET	Wave erosion of slope toe	Ongoing and periodic wave erosion of earth slopes below tracks causing oversteepening
TFE	Through flow erosion	Material can be removed from below by solution, seepage erosion or piping affectively loosening the earth deposit and may increase the earth landslide hazard
D	Denudation	The process by which a slope is stripped bare of vegetation by the processes of weathering transportation or erosion. Makes the slope more susceptible to infiltration increasing the earth landslide hazard
F	Fires	Removal of the forest cover by fire in the vicinity of the tracks increases the railway earth landslide hazards by: • Decreasing evapotransporation, • Loss of soil suction • Loss of root binding and protection, • Increasing runoff, • Increasing infiltration • Increasing potential of blocked, redirected or concentrated drainage (culverts, ditches, bridges)

Preparatory Causal Factors - earth landslides		**Description**
VR	Vegetation removal	Removal of vegetation by natural means such as forest fire, drought, wind or previous debris flows can increase water infiltration, remove the stitching affect of roots and decreases evapotranspiration.
3.Physical Processes		
LLISM	Low level Intense snow melt	Provides rapid recharge of water into the earth in proximity of the track reducing effective stress and shear strength. As a preparatory causal factor a time lag is associated with the snow melt event
SAR	Significant antecedent rainfall	Causes an abundance of free water saturating earth causing water pressure build up reducing effective stress and shear strength increasing the earth landslide hazard. As a preparatory causal factor the antecedent rainfall only brings the slope closer to failure.
IR	Intense rainfall	Causes an abundance of free surface water filling cracks introducing thrust forces within the potential slide mass and saturating earth causing water pressure build up reducing effective stress increasing the earth landslide hazard. As a preparatory cause the intense rainfall only brings the slope closer to failure.
HGR	High groundwater recharge	Causes a build up of water pressures and steepens the hydraulic gradient in the earth slope resulting in reduced effective stress, thrust forces in water filled cracks and high seepage forces increasing the earth landslide hazard
T	Thawing	Thawing of earth slopes inwards resulting in reduction in negative pore pressures and saturation in the slope causing an earth landslide hazard.
WD	Wet and drying weathering	Cycles of wet and dry may cause loss of suction in unsaturated zone of non-cohesive earth causing an earth landslide hazard.
SS	Shrink and swell weathering	Cycles of wet and dry may cause desiccation of a clay rich earth allowing rapid influx of water increasing the earth landslide hazard

Preparatory Causal Factors - earth landslides		**Description**
EPP	Excess pore pressures	A rapid recharge of ground water or excess surcharge loading can result in excess pore pressures above hydrostatic reducing effective stresses in the slope decreasing the slope stability.
ESF	Elevated seepage forces	Elevated seepage forces within the slope from groundwater flows parallel to the slope surface can reduce the slope stability.
ESF	Elevated stream flows	Stream erosion at the toe of a slope brought on by elevated stream flows will reduce the slope stability. The water loading afforded by the elevated water level commonly offsets this causal factor and the affects of the erosion are not realized until the water level has receded.
RD	Rapid draw-down	Elevated pore pressures in the slope lag behind a rapid lowering of the water level and associated removal of the water loading on the slope reducing the slope stability.
4.Man-made or Animal Processes		
OS	Over steepening	Excavation of earth slopes at the toe imposes an additional artificial over-steepening of earth slopes decreasing slope stability
SOL	Shoulder loading	Placement of waste material on track roadbed shoulder or dumped over bank increases loading on the earth slope and steepens the slope increasing the destabilizing forces and blocks seepage bringing the slope closer to failure.
VR	Vegetation removal	Deforestation or vegetation denudation of upper slopes and rock slopes increases infiltration of water into the groundwater, reduces evapotranspiration and suction provided by the trees and plants.
Ir	Irrigation	Increases groundwater recharge to the earth slope resulting in reduced effective stress. Thrust forces bring the earth slope closer to failure in the form of a earth landslide.

Preparatory Causal Factors - earth landslides		Description
WLU	Water leakage from utilities	Increases groundwater recharge to the earth slope resulting in reduced effective stress. Thrust forces bring the earth slope closer to failure in the form of a earth landslide.
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can increase groundwater recharge to the earth slopes resulting in reduced effective stress. Thrust forces bring the earth slope closer to failure in the form of a earth landslide.
BA	Beaver activity	Beaver habitat in the vicinity of the tracks predisposes the track to beavers increasing the earth slide or flow hazard by the impoundment of water against the railway embankment (rapid draw down) or increasing likelihood of hydraulic erosion at the toe of the railway embankment.
TA	Train action	The cyclic dynamic and dead loading from a freight train can cause incremental strains that bring an earth slope closer to failure.

8.7 Earth Landslide Hazard Scenarios Trigger Causal Factors

8.7.1 Observed Earth Landslide Hazard Scenario Trigger Causal Factors

Error! Reference source not found. presents the trigger causal factors identified by the author for each earth landslide hazard scenario inspected. Table 8-7 provides a summary of the most prevalent trigger causal factors taken from the results presented in **Error! Reference source not found.**.

As a group *intense rain*, *prolonged rain* (significant antecedent rain), *snow melt*, *high water table* (elevated phreatic surface), and *thaw* are the most commonly reported trigger causal factors for earth landslide scenarios.

The common denominator for these trigger causal factors is that they represent influx of water into an earth slope system and thus can shift the earth slide hazard from a *marginal* or *suspended* to an *active* or *reactivated* activity stage (see Section 4.4.5.3). The influx of water can reduce the slope stability by either filling cracks introducing thrust forces into the slide mass or increasing pore pressures reducing the effective stresses within the slope or on pre-existing rupture surfaces. External loads such as train loading overloading the crest and removal of toe material by excavation or erosion are commonly known trigger causal factors for earth landslides.

Wind and train vibrations were observed as a trigger causal factor for earth falls.

An additional trigger causal factor of freeze / thaw was reported for Earth Slide – Earth Fall scenarios. This stems from the case example derailment incident presented in Figure 8-12 in Section 8.2.6 in which case the event occurred after the first full day of freezing temperatures in the fall. Since the event occurred during the night it is suggested the volumetric increase from freezing of water in near surface cracks triggered the earth slide.

Level III Subgroups	Ground Hazard Scenario	Count	Intense Rain	Prolonged Rain	High Water	High Water Table	Piping	Freeze/Thaw	Snow Melt	Raising Freezing Level	Rapid Drawdown	Heavy Snow	Thaw	Anthropogenic
Earth Landslides	**Earth Landslides**													
	Earth (Embankment) Slide	90	48%	58%	2%	18%	0%	2%	59%	0%	0%	0%	38%	0
	Earth Slide	65	45%	62%	8%	25%	0%	3%	57%	0%	0%	0%	20%	0
	Earth Slide - Earth Flow	4	75%	100%	25%	100%	25%	0%	75%	0%	0%	0%	50%	0
	Earth (Embankment) Slide - Earth Flow	4	100%	100%	0%	100%	0%	0%	100%	100%	0%	0%	0%	100
	Earth (Embankment) Slide - Compression	4	75%	75%	0%	25%	0%	0%	50%	0%	0%	0%	25%	0
	Earth Slide - Earth Fall	3	100%	100%	0%	33%	0%	100%	100%	0%	0%	0%	0%	33
	Subtotal	**170**	**50%**	**62%**	**5%**	**25%**	**1%**	**4%**	**60%**	**2%**	**0%**	**0%**	**29%**	**3**

Table 8-6 Trigger causal factors identified for each Earth Landslide hazard scenario identified. The percentage each trigger causal factor was reported for each hazard scenario is presented.

Table 8-7 Summary of prevalent earth landslide trigger causal factors identified according to the functional earth landslide hazard scenario subgroups.

Earth Landslide Hazard Scenario	Prevalent Trigger Causal Factors Identified	
Earth(Embankment) Slide	• Intense rain • Significant antecedent rain • Elevated phreatic level • Snow melt	• Rain on snow* • Thaw • Train Action
Earth Slide	• Intense rain • Significant antecedent rain • Elevated phreatic level	• Snow melt • Thaw • Rain on snow*
Earth Slide - Earth Flow	• Intense rain • Significant antecedent rain • High water • Elevated phreatic level	• Piping • Snow melt • Rain on snow* • Thaw
Earth (Embankment) Slide - Earth Flow	• Intense rain • Significant antecedent rain • Elevated phreatic level • Snow melt	• Rain on snow* • Raising freezing level • Anthropgenic • Train action
Earth (Embankment) Slide - Compression	• Intense rain (ballast trough) • Significant antecedent rain • Elevated phreatic level • Snow melt	• Rain on snow* • Thaw • Train action
Earth Slide - Earth Fall	• Intense rain • Significant antecedent rain • Elevated phreatic level • Freeze/thaw	• Snow melt • Rain on snow* • Anthropgenic
Overall Earth Landslide Hazard Scenarios	• Intense rain • Significant antecedent rain • Elevated phreatic level • Snow melt	• rain on snow* • Thaw • Train action

* Inferred trigger causal factor given that both intense rain and snow melt are identified

8.7.2 Suggested Earth Landslide Events Trigger Causal Factors

Table 8-8 provides the author's suggested glossary and description of the trigger causal factors for earth landslide events.

Table 8-8 Suggested railway earth landslide hazard trigger causal factors.

Trigger Causal Factors – Earth landslides		Description
1.Geomorphological Processes		
FET	Fluvial erosion of slope toe	Ongoing or periodic stream erosion of earth slopes below and above the tracks causing over-steepening
WET	Wave erosion of slope toe	Ongoing and periodic wave erosion of earth slopes below tracks causing over-steepening
SE	Through flow erosion	Material can be removed from below by solution, seepage erosion or piping affectively loosening the earth deposit and may induce the earth landslide event
VR	Vegetation removal	Removal of vegetation by natural means such as forest fire, drought, wind or previous debris flows can increase water infiltration, remove the stitching affect of roots and decreases evapotranspiration.
2.Physical Processes		
LLISM	Low level Intense snow melt	Provides rapid recharge of water into the earth reducing effective stress and shear strength or filling cracks introducing destabilizing thrust forces.
SAR	Significant antecedent rainfall	Causes an abundance of free water saturating earth causing pore water pressure build up reducing effective stress and shear strength increasing the earth landslide hazard. As a trigger causal factor the antecedent rainfall brings the slope to failure.
IR	Intense rainfall	Causes an abundance of free surface water filling cracks introducing thrust forces within the potential slide mass and saturating earth causing water pressure build up reducing effective stress causing the earth landslide event.

Trigger Causal Factors – Earth landslides		Description
HGR	High groundwater recharge	Causes a build up of water pressures and steepens the hydraulic gradient in the earth slope resulting in reduced effective stress, thrust forces in water filled cracks and high seepage forces causing the earth landslide event.
T	Thawing	Thawing of earth slopes inwards resulting in reduction in negative pore pressures and saturation in the slope causing an earth landslide event.
WD	Wet and drying weathering	Cycles of wet and dry may cause loss of suction in unsaturated zone of non-cohesive earth causing an earth landslide event.
EPP	Excess pore pressures	A rapid recharge of ground water or excess surcharge loading can result in excess pore pressures above hydrostatic reducing effective stresses in the slope decreasing the slope stability.
ESF	Elevated seepage forces	Elevated seepage forces within the slope from groundwater flows parallel to the slope surface can reduce the slope stability.
ESF	Elevated stream flows	Stream erosion at the toe of a slope brought on by elevated stream flows will reduce the slope stability. The water loading afforded by the elevated water level commonly offsets this causal factor and the affects of the erosion are not realized until the water level has receded.
RD	Rapid draw-down	Elevated pore pressures in the slope lag behind a rapid lowering of the water level and associated removal of the water loading on the slope reducing the slope stability.
3.Man-made or Animal Processes		
OS	Steepening	Excavation of earth slopes at the toe imposes an additional artificial steepening of earth slopes decreasing slope stability causing an earth landslide
SOL	Shoulder over loading	Placement of waste material on track roadbed shoulder or dumped over bank increases loading on the earth slope and oversteepens the slope increasing the destabilizing forces and potentially blocks seepage bringing the slope to failure.

Trigger Causal Factors – Earth landslides		**Description**
Ir	Irrigation	Increases groundwater recharge to the earth slope resulting in reduced effective stress. Thrust forces bring the earth slope closer to failure in the form of a earth landslide.
WLU	Water leakage from utilities	Increases groundwater recharge to the earth slope resulting in reduced effective stress. Thrust forces bring the earth slope closer to failure in the form of a earth landslide.
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can increase groundwater recharge to the earth slopes resulting in reduced effective stress. Thrust forces bring the earth slope closer to failure in the form of a earth landslide.
BDB	Beaver dam burst	A beaver dam burst upstream or downstream of the tracks due to deterioration or inadequate construction of a dam or high flows in the channel can trigger an earth slide or flow event by rapid draw down from release of impounded water or hydraulic erosion at the toe of an embankment.
TA	Train action	The cyclic dynamic and dead loading from a freight train can bring an earth slope to failure.

8.8 Attributes for Earth Landslide Scenarios

Consistent with the range of soil types contained in the earth material category there is a diverse range of landforms that contain them. This list becomes much shorter when we consider only the landforms where the more common earth landslides that affect railways occur.Table 8-9 lists the more common earth landslide events described in Section 8.3 and suggests the associated soil type and landform attributes for each of them.

Table 8-9 List of landforms associated with earth landslide hazards

Earth Landslide Hazard	**Landform**
Very rapid earth falls (ravelling)	Occurs in ML, SC, SM, SP, SW as an earth fall in the following land forms: fluvial, lacustrine, glacio fluvial, glacio lacustrine, moraine, colluvium, ditch spoils, and cuts and fills.
Earth slide-earth fall	Occurs commonly in steep or undermined ML, SC, SM and SP in the following land forms: natural earth slopes on colluvial cones or cuts, sections of river bank undergoing persistent bank erosion or recent stream avulsion.
Rotational earth slides	Occurs in predominantly homogenous weak earth deposits such as CH, MH, OL, CL and ML commonly found in the following landforms: lacustrine, glacio lacustrine, moraine, ditch spoils anthropogenic cuts and fills. Mass movement features such as arc shaped scarps or backtilt of grabens.
Translational earth slides	Occurs commonly in natural deposits following weak layers in the stratigraphy such as CH, MH, OL, CL and ML layers or a sloping bedrock surface. Common landforms include cuts into buried channel deposits, soil veneers over shallow, sloping bedrock, mass movement features such as planer shaped scarps or lack of back-tilted grabens.
Compound earth slides	Occurs commonly in natural and anthropogenic deposits with inhomogeneities in the stratigraphy such as CH, MH, OL, CL and ML layers or a sloping bedrock surface. Common landforms include cuts into buried channel deposits, soil veneers over shallow, sloping bedrock. Mass movement features such as arc shaped scarps near the head scarp and linear uphill facing scarps down slope or back-tilted grabens up slope and lack of same down slope.
Earth slide-earth flow	Occurs commonly in natural and anthropogenic deposits of ML, SC, SM, SP, SW. Common landforms containing these soils include eolian, lacustrine, glacio lacustrine, fluvial, deltaic, moraine, ditch spoils, cuts and fills.
Earth flows	The soil groups most associated with earth flows include saturated, loose SM and ML materials and highly sensitive or quick clay materials. Common landforms containing these soils include eolian, lacustrine, glacio lacustrine, fluvial, deltaic, moraine, ditch spoils, cuts and fills.
Earth (peat) Spreads (corduroy failures)	Associated with earth embankments across peat bog land forms.

8.9 Earth Landslide Hazard Scenarios Consequence Likelihood Factors

8.9.1 Track Vulnerability

The vulnerability of the track and track structures to earth landslide events depends on factors including the size, material types, speed, relative location and length of run out. As well it depends on avoidance factors such as train speed, track geometry, line of sight and warning devices. Table 8-10 summarizes the author's list of suggested track vulnerability factors corresponding to the mode of track failure and the type of earth landslide.

Table 8-10 Listing of the track failure attributes corresponding to the modes of track failure and earth landslide hazard events.

Modes of Track Failure *…. ground hazards may cause a track failure by:*	**Causative Ground Hazards**	**Track Vulnerability Factors**
Removing support from the track structure;	• Earth slides, spreads, flows	• Presence of retaining structures or bridges • Size, gradation and compaction of subgrade material. • Shoulder width • Ballast, sub ballast quality • Presence of revetment • Track drainage
Blocking the track;	• Earth slides, spreads, flows	• Ability to retain material (barrier walls, catch fences, ditch catchment, deflection berms) • Ditch catchment • Particle size, volume and distribution of material blocking track
Striking a train;	• Earth slides, flows	• Ability for material to pass over or under tracks (bridges, culverts, flumes, sheds) • Ditch catchment
Deflecting the track rail surface,	• Earth slides, spreads, flows	• Track geometry (curves and spirals are more susceptible) • Train loading • Track surface • Shoulder width • Ballast, sub ballast quality

Modes of Track Failure *.... ground hazards may cause a track failure by:*	**Causative Ground Hazards**	**Track Vulnerability Factors**
Damaging track structures (such as bridges, retaining walls or sheds)	- Earth slides	- Location, shape, orientation, and foundation type of bridge piers and abutments. - Type of retaining wall (Tie-back, cantilever, gravity)

8.9.2 Service Disruption Vulnerability

The main service disruption vulnerability factors for earth landslide scenarios given that track failure has occurred include presence or absence of warning devices such slide detector fences or tip over posts, train speed, sight lines, grades, presence or absence of central traffic control circuit in the tracks and traffic frequency. More details on these factors is given in Section 4.6.2.

8.9.3 Derailment Vulnerability

The derailment vulnerability factors for earth landslide scenarios given that track failure has occurred include presence or absence of warning devices such slide detector fences, train speed, sight lines, grades, presence or absence of central traffic control circuit in the tracks and traffic frequency. More details on these factors are given in Section 4.6.3.

8.10 Summary

From Chapter 3, accidents attributable ultimately to earth landslides, occurred at an average frequency of 3.2 per year, with $698,000 direct costs per accident, accounting for $2,220,000 per annum, occurring mainly on the CN Edmonton to Vancouver, with the most severe event being the Conrad derailment in March of 1997 ($10M direct costs). Losses from accidents attributable to earth landslide initiated hazard scenarios, occurred at a frequency of 1.91 per year, a severity of $875,000, amounting to $1,671,000 per annum. The chapter characterizes the identified earth landslide hazard scenarios from the CN Western Canada ground hazard database that contributed to these loss records.

53% of the earth landslide hazard sites simple Earth (Embankment) Slide scenarios; 38% are simple Earth Slides scenarios, and the remaining 9% are evenly split between Earth Slide - Earth Flow, Earth (Embankment) Slide - Earth Flow, Earth (Embankment) Slide - Compression and Earth Slide - Earth Fall hazard scenarios.

Earth (Embankment) Slide hazard scenarios are simple earth slides of railway embankment. The rupture surface contained in the embankment material, or in the weaker foundation soil, commonly start with minor movements and move incrementally with train loading, are treated initially by intermittently lifting and surfacing the track. Track failure occurs by removal of track support, track deflection, or damaging track structures.

Earth Slide hazard scenarios typically involve existing slides, that have developed in natural deposits above, below or under the tracks. Track failure occurs by removal of track support, track deflection, blockage or damaging track structures.

Earth Slide – Earth Flow hazard scenario typically involves earth slides in silty material from the upper slope. The saturated slide mass converts to a flow, and the speed and mobility of the flow depends on the length and gradient of the run out path. The scenario is illustrated using a case example near Abbottsford, BC, which demonstrates the speed and mobility these flows can have. Track failure occurs by blockage, deflecting the track surface, striking a train or removing track support.

Earth (Embankment) Slide – Earth Flow hazard scenarios typically involve a rapid influx of water into the track non-cohesive embankment from either overland flow or through flow causing a rise in the phreatic surface and a steep hydraulic gradient in the lower slope. The saturated non-cohesive slide mass converts to a flow and the speed and mobility of the flow depends on the length and gradient of the run out path. A case example of the fatal derailment at Mile 106.14 on the CN Ashcroft Subdivision illustrates the very rapid movement and high mobility these scenarios can exhibit. Identification is difficult as they show little distress until the triggering causal factors occur. Track failure occurs by removing track support or deflecting the track surface.

Earth (Embankment) Slide – Compression hazard scenarios typically involve an overly thick section of ballast usually on one side of the track resulting from a long period of track lifting required due to slow or incremental reactivations of a pre-existing earth (embankment) slide. The thick section of loose ballast lacks lateral resistance and is subject to compression settlement during train loading. Track failure occurs by removing track support or deflecting the track surface.

Earth Slide – Earth Fall hazard scenarios typically initiate from above the tracks with a slide of a more or less coherent block of earth that, once detached from its source area, falls, bounces or rolls fragmenting along its trajectory. The case example illustrates these scenarios typically originate from weakly cemented over steepened earth slopes that loose their cohesion after detachment. Track failure occurs by either blocking the track or striking a train.

Earth soil contains at least 80 percent particles smaller than 2 mm which includes sands, silts, clays and highly organic soils. Highly organic soils contains greater than 20 percent organic material by volume. Earth soil's diversity of engineering properties results in a diversity of failure characteristics associated with the landslides, that involve them. In characterizing earth landslides, it is essential to identify the particular soil earth group involved and understand their properties.

Earth falls involve detachment of single earth particles (ravelling), many particles or as a coherent lightly cemented mass which then descends by free fall, bouncing or rolling. Movements are very rapid to extremely rapid. Ravelling occurs in an incremental, progressive fashion from various triggers. It can retrogress to undermine the track sub-grade and be a significant safety risk to personnel below.

Earth slides involve movement of an earth mass on rotational, translational or compound surfaces of intense shear strain. Movement rates range from extremely slow to very rapid due to earth soils diversity of physical properties

Rotational earth slides move on curved or concave surfaces most frequently in homogeneous material with little internal deformation resulting in a near vertically downward and back tilting of the head of the displaced mass and a bulging out in the toe area. Rotational movements can restore the displaced mass to equilibrium which can be disturbed by loading at the head, unloading at the toe or a reduction in shear strength along the rupture surface. Rotational earth slide localized to the track sub-grade commonly occur in low, clay embankments caused by the incrementally applied loads of trains.

Translational earth slides move along planar or undulating surfaces of rupture sliding out over the original ground surface. They are associated with planer discontinuities such as shallow planar pre-existing shears or shallow sloping bedrock surfaces and inhomogeneities such as shallow, planar, weak layers.

Compound earth slides move along an apparent combination of rotational and translational rupture surface usually controlled by a weak layer at depth. Kinematics infer these earth slides initiate as a series of wedges with tangential rupture surfaces with the rotational shape developed only after large shear strains in the back rupture surface. These slides are notorious for rapid and mobile retrogressive movements associated with post glacial degradation of rivers in pre glacial buried river channel deposits.

A case example of a compound earth slide at CN Ashcroft Mile 50.9 illustrates the complex interaction between postglacial degradation of river systems and landslide movements as well as the controlling aspects of the weak soil layer at depth.

Earth flows resemble the movements of a viscous fluid in an earth slope. Where the velocity is greatest at the surface and decreases downward in the flowing mass. Earth flow movement velocities can range from very slow to very rapid. Saturated loose SM and ML materials and high sensitive or quick clay materials have the highest potential to form rapid to very rapid earth flows.

Earth slide-earth flow and earth (embankment) slide-earth flow hazard events can result in catastrophic failure of the railway grade as illustrated in the Conrad earth (embankment) slide-earth flow case example. The preparatory causal factor suggested is a high phreatic surface in a slope of loose or contractive fine non-cohesive soils. Railway embankments are prone to this type of failure due to the nature of their construction and maintenance which results in a pervious granular material under the tracks and SM or ML material on the downstream slope. Events are triggered by a rapid and sustained overland/through flow influx of water into the embankment resulting in a quick rise in the phreatic surface under the tracks and a steep hydraulic gradient is set up within the downstream slope. The resulting landslide typically starts as an earth slide but the slide mass quickly looses cohesion converting to an earth flow. A second case history at CN Robson Subdivision Mile 10.2 illustrates this type of landslide triggered by rapid influx from overland flow.

Earth spreads involve an extension of a cohesive earth soil mass combined with a gentle subsidence of the fractured mass of into softer underlying material. The only earth spread events are contained in the Consolidation – Earth (peat) Spread hazard scenario and involves failure of the stiffer granular embankment into the much softer peat substrata. The base of these embankments was made stiffer with the placement of crisscrossing trees at the base of the embankments referred to as Corduroy. It is suggested an earth (peat) spread involves a rapid tearing of the decomposed corduroy typically under train loading followed by a rapid, not gentle, subsidence of the fractured earth embankment into the much softer peat. This is illustrated in two case examples.

Observations indicate that rates of track failure range from slow to rapid for Earth (embankment) Slide or Earth Slide scenarios the estimated however pre track failure movements tend to be very slow or incremental inferring cohesive soils control the movements. Earth flows or falls are estimated as rapid to very rapid consistent with saturated non cohesive or work softening soils control the movements. Quick marine clays are not known to affect CN tracks in Western Canada but would be rapid to very rapid movements.

The suggested trigger causal factors that control timing of ESl are significant antecedent rain, snow melt and incremental train and for ESl-EFw events are significant antecedent or intense rain or snow melt. For ESl-EF the timing of EF events depends on freeze/thaw causal factors. Lag time between ESl-EFw events is estimated as minutes to hours, between E(Em)Sl - Cm as months to years and between ESl – EF events as seconds.

As ESl, E(Em)Sl and E(Em)Sl - Cm scenarios are reactivated slides, they exist in the (2) Marginally Stable to (3) Stable – monitoring required track stability states. Buttress berms, shear keys and some drainage works can move these scenario to a (4) Stable track stability state after moitoring for one cycle of seasons. Track stability states for hard to identify ESl-EFw and E (Em) Sl-EFw scenarios can be indirectly estimated using real time climatic trigger causal factors.

Observed preparatory causal factors for ESl, E(Em)Sl and E(Em)Sl - Cm hazard scenarios are a depleted shoulder, incremental train loading and ballast trough.

Observed preparatory causal factors for ESl-EFw and E (Em) Sl-EFw scenarios is seepage erosion, plugged ditches, poor culvert inlet arrangement and presence of non-cohesive fines. A case example of an ESl-EFw event at Mile 151.4 CN's Edson Subdivision illustrates elevated phreatic surface, increased seepage and elevated hydraulic gradient preparatory causal factors that brought the track to a (2) marginally stable state. Train loading triggered the track failure.

Observed preparatory causal factors for the ESI-EF hazard scenario include piping, slope wash or seepage erosion.

Suggested preparatory causal factors for earth landslides include:

Ground Conditions:

- Quaternary Glaciation Materials
- Contrast in permeability
- Contrast in stiffness
- Homogenous weak earth deposits
- Corduroy

Physical Processes

- Low level Intense snow melt
- Significant antecedent rainfall
- Intense rainfall
- High groundwater recharge
- Earthquake
- Thawing
- Wet and drying weathering
- Shrink and swell weathering
- Excess pore pressures
- Elevated seepage forces
- Elevated stream flows
- Rapid draw-down

Geomorphological Processes

- Fluvial erosion of slope toe
- Wave erosion of slope toe
- Through flow erosion
- Denudation
- Fires
- Vegetation removal

Man-made or animal processes

- Steepening
- Shoulder over loading
- Vegetation removal
- Irrigation
- Water leakage from utilities
- Blocked drainage
- Beaver activity
- Train action

The predominant observed trigger causal factors for earth slide and flow scenarios were intense rain, significant antecedent rain, snow melt, elevated phreatic surface, and thaw all of which cause an influx of free water to the earth slope system reducing the slope stability by filling cracks introducing thrust forces into the slide mass or increasing pore pressures reducing the effective stresses within the slope or on pre-existing rupture surfaces. External loads and removal of toe material are commonly known trigger causal factors for earth landslides.

Freeze / thaw trigger causal factors are reported for Earth Slide – Earth Fall scenarios.

A tabular summary of prevalent earth landslide trigger causal factors is provided for each of the six earth landslide scenarios.

Suggested trigger causal factors for earth landslides include:

Geomorphological Processes

- Fluvial erosion of slope toe
- Wave erosion of slope toe
- Through flow erosion
- Vegetation removal

Man-made or animal processes

- Steepening
- Shoulder over loading
- Irrigation
- Water leakage from utilities
- Blocked drainage
- Beaver dam burst
- Train action

Physical Processes

- Low level Intense snow melt
- Significant antecedent rainfall
- Intense rainfall
- High groundwater recharge
- Earthquake
- Thawing
- Wet and drying weathering
- Excess pore pressures
- Elevated seepage forces
- Elevated stream flows
- Rapid draw-down

The more common earth landslide events are associated with the typical landforms they occur in. Very rapid earth falls (ravelling) occur in fluvial, lacustrine, glacio fluvial, glacio lacustrine, moraine, colluvium, ditch spoils, and anthropogenic cuts and fills

Earth slide-earth falls occur in oversteep natural earth slopes with associated colluvial cone (such as "hoodoos") or anthropogenic cuts, sections of river bank undergoing persistent bank erosion or recent stream avulsion.

Rotational earth slides occur in lacustrine, glacio lacustrine, moraine, ditch spoils anthropogenic cuts and fills, and mass movement features such as arc shaped scarps or back-tilt of slipped masses.

Translational earth slides occur in cuts into buried channel deposits, soil veneers over shallow, sloping bedrock, mass movement features such as non arc shaped scarps or lack of back-tilted slipped masses.

Compound earth slides occur in cuts into buried channel deposits, soil veneers over shallow, sloping bedrock, and mass movement features such as arc shaped scarps near the head scarp and linear scarps down slope or back-tilted slipped masses up slope and lack of same down slope.

Earth slide-earth flows and Earth flows occur in eolian, lacustrine, glacio lacustrine, fluvial, deltaic, moraine, ditch spoils anthropogenic cuts and fills.

Earth (peat) Spreads occur in earth embankments across peat bog land forms

Track vulnerability factors specific to the earth landslide event include the size, material types, speed, relative location and length of run out. Track vulnerability factors in the vicinity of the track structure are correlated to the mode of track failure and the type of earth landslide. The track specific vulnerability factors suggested include presence, location, shape, orientation, and foundation type of retaining structures or bridges; size, gradation and compaction of subgrade material; shoulder width; ballast, sub ballast quality; presence of revetment; track drainage; affective catchment; particle size, volume and distribution of material blocking track; ability for material to pass over or under tracks; track geometry; train loading; and track surface.

Suggested service disruption vulnerability factors for debris landslide scenarios include presence of warning devices, train speed, sight lines, grades, presence of central traffic control and traffic frequency.

Suggested derailment vulnerability factors for earth landslide scenarios include presence of warning devices, train speed, sight lines, grades, presence of central traffic control and traffic frequency

Chapter 9 Characterization of Railway Subsidence Hazard Scenarios: CN Western Canada

9.1 Introduction

Subsidence is defined as a downward displacement of the track roadbed associated with compression or displacement of materials in the embankment or the underlying foundation. Settlement is a slow process resulting from compression, consolidation, plastic deformation or incremental dynamic liquefaction. Collapse is a rapid occurrence associated with vertical displacement into a void. From Chapter 3, between 1992 and 2002, train accidents attributable to settlement hazard events occurred with an average frequency of 1.4 per year, with $28,000 direct costs per accident accounting for approximately $40,000 per annum. Settlement is more prevalent on the Interior Plains with the majority of the incidents occurring in the Saskatoon to Calgary corridor (due to the abundance of weak clay subgrades and the lack of drainage in this low relief area). The only incident in the record which may be attributed to a collapse event is the Orient Bay derailment (TSB, 1996), which is suggested to involve collapse of the track subgrade into piping voids, formed previously in non-cohesive calcareous lacustrine silt.

This chapter steps through the characterization of the identified subsidence hazard scenarios from the CN Western Canada ground hazard database that would have contributed to these loss records. Following an illustration and description of the hazard scenarios initiating with subsidence events, the chapter characterizes subsidence ground conditions and processes, rates and timing of system failure and track stability states. This is followed by identification and characterization of subsidence hazard events preparatory and trigger causal factors either the author have observed or interpreted followed with an identification of subsidence revealing factors. The chapter closes with a summary of subsidence landslide hazard scenarios consequence likelihood factors for track failure, service disruption and derailment.

9.2 Subsidence Hazard Scenarios Failure Mode and Effect Analysis.

The short list of identified hazard scenarios initiating with subsidence events is presented in Table 9-1. The eight scenarios identified are subdivided into 4 subgroups namely *subgrade plastic deformation containing* 39% of the hazard locations, *consolidation* containing 33% of the hazard locations, *compression containing* 25% of the hazard locations *and sub-grade dynamic liquefaction* containing 3% of the hazard locations. Sub-grade dynamic liquefaction hazards also referred to as “mud spots” in the track were managed by the track maintenance personnel and thus not systematically identified during the inspections. Thus the relatively low number of identified locations is not representative.

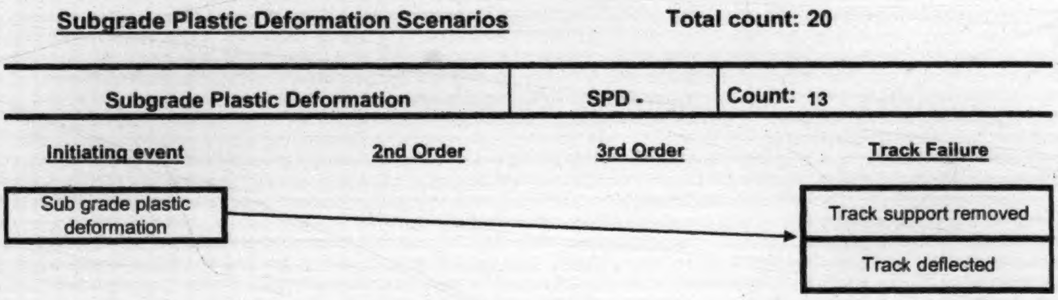
Table 9-1 Summary of subsidence hazard scenarios CN Western Canada

Level III Subgroups	**Ground Hazard Scenario**	**Coding**	**Count**
Settlement	**Subgrade Plastic Deformation**		
	Subgrade Plastic Deformation	SPD -	13
	Subgrade Plastic Deformation – Earth(Embankment) Slide	SPD - E(Em)Sl -	7
		Subtotal	20
	Consolidation		
	Consolidation - Compression	Cn - Cm -	9
	Consolidation - Earth Spread	Cn - E(Pt)Sp -	4
	Consolidation – Compression (peat)	Cn - Cm(Pt) -	4
		Subtotal	17
	Compression		
	Compression	Cm -	13
		Subtotal	13
	Subgrade Dynamic Liquifaction		
	Subgrade Dynamic Liquifaction	SDL -	2
	Subgrade Dynamic Liquifaction - Earth Slide	SDL - ESl -	2
		Subtotal	4
		Total Subsidence Hazard Scenario Hazards	54

Of relevance is that there were no hazard scenarios identified in the database initiating with collapse events. Collapse events are included in identified hazard scenarios initiating with overland / through flow erosion events presented in Chapter 10. Following is an illustration and description of the failure mode and effect analysis (FMEA) for each of the identified subsidence scenarios. As well collapse hazard events are described in Section 9.3.

9.2.1 Subgrade Plastic Deformation Scenarios

Figure 9-1 and Figure 9-2 depict the simplified FMEA for Subgrade Plastic Deformation and Subgrade Plastic Deformation – Earth (embankment) Slide, the two hazard scenarios in this subgroup. Recall that subgrade plastic deformation involves incremental plastic deformation and settlement of the track resulting from local over-stressing and incremental plastic deformations of clay sub-grades from repetitive train loads. The fundamental difference between these scenarios and the reason for the distinction between them is that simple Subgrade Plastic Deformation scenarios occur on flat ground whereas Subgrade Plastic Deformation – Earth (embankment) Slide scenarios occur on a cohesive embankment. In the latter scenario there is a potential that, as a result of excessive subgrade plastic deformation, a rupture surface can form through the embankment fill. Both these scenarios can cause track failure by either removing support from the track structure or deflecting the track surface.


Subgrade Plastic Deformation Scenarios
Total count: 20
Subgrade Plastic Deformation
SPD -
Count: 13
Initiating event
2nd Order
3rd Order
Track Failure
Sub grade plastic deformation
Track support removed
Track deflected

Notes: 1. SPD occurring in cohesive subgrade

Figure 9-1 Simplified FMEA for the Subgrade Plastic Deformation hazard scenario

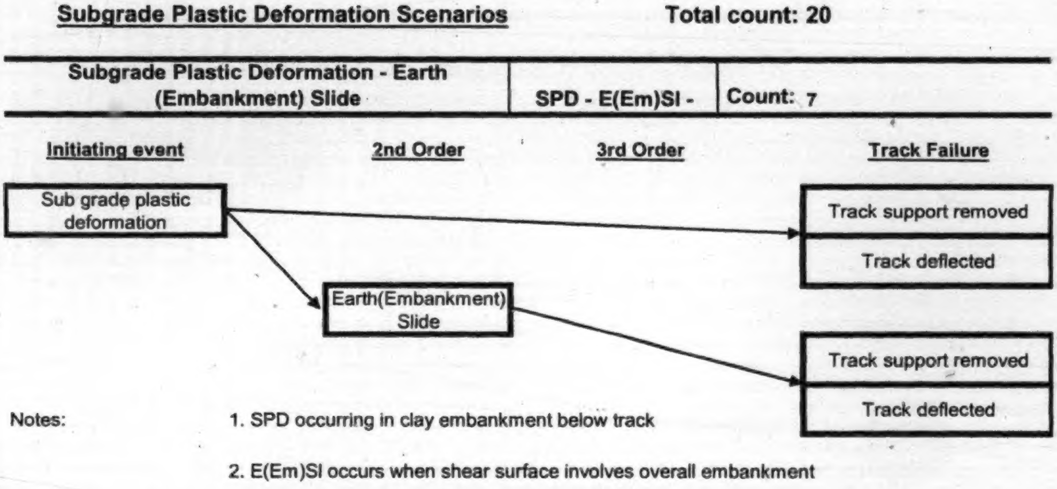
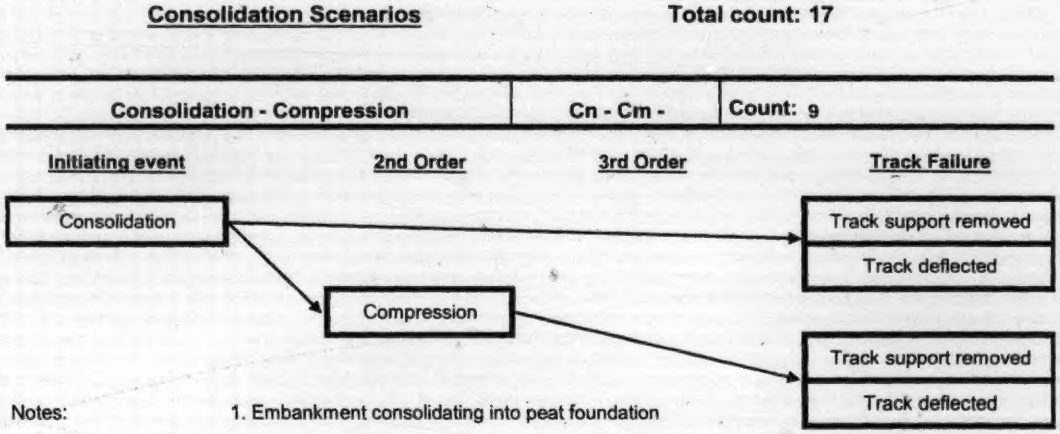

Subgrade Plastic Deformation Scenarios
Total count: 20
Subgrade Plastic Deformation - Earth (Embankment) Slide
SPD - E(Em)Sl -
Count: 7
Initiating event
2nd Order
3rd Order
Track Failure
Sub grade plastic deformation
Track support removed
Track deflected
Earth(Embankment) Slide
Track support removed
Track deflected
Notes:
1. SPD occurring in clay embankment below track
2. E(Em)Sl occurs when shear surface involves overall embankment

Figure 9-2 Simplified FMEA for the Subgrade Plastic Deformation – Earth (embankment) Slide hazard scenario.

9.2.2 Consolidation Scenarios

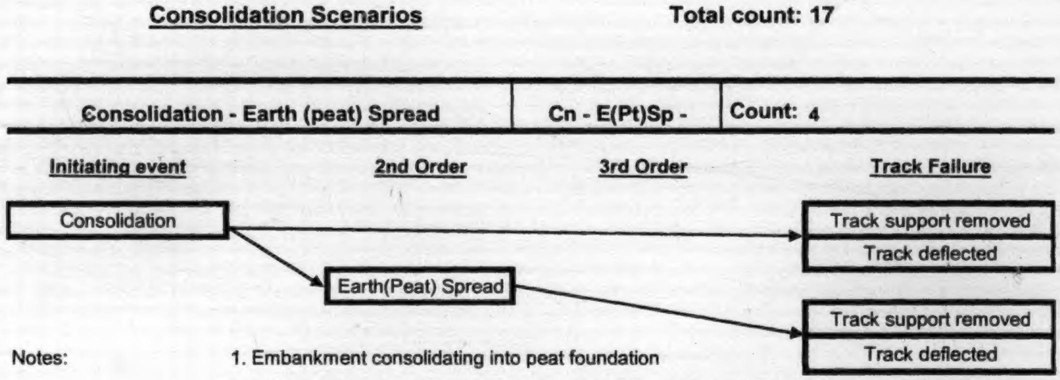
Figure 9-3, Figure 9-4 and Figure 9-5 depict the simplified FMEA for Consolidation – Compression, Consolidation – Earth (peat) Spread and Consolidation – Compression (peat), the three hazard scenarios in this subgroup. Consolidation hazard events refer to embankments placed across organic terrain (muskeg) and soft compressible clays which can settle slowly for many years, responding to the consolidation characteristics of the organic or clay soils and to compositional changes (organic decay) occurring in the foundation. A review of the records indicates all of these sites from all three scenarios involve embankment fills over peat foundations. The fundamental difference between the scenarios is that embankments for the Consolidation – Compression scenarios do not show any signs of distress and only the high ballast section is of concern. With the Consolidation – Earth (peat) Spread scenarios the embankments typically show some form of distress suggesting a rupture surface may have formed through the embankment fill. Finally the Consolidation – Compression (peat) scenario involves jostling of the track during train action due to the spongy or low stiffness elastic compression of the fully consolidated peat substrata. All these scenarios can cause track failure by either removing support from the track structure or deflecting the track surface. The Consolidation – Compression (peat) scenario can also cause track failure by damaging the track components due to the jostling action as described in Section 9.3.2.


Consolidation Scenarios
Total count: 17
Consolidation - Compression
Cn - Cm -
Count: 9
Initiating event
2nd Order
3rd Order
Track Failure
Consolidation
Compression
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. Embankment consolidating into peat foundation
2. Compression hazard event from overly thick ballast section.

Figure 9-3 Simplified FMEA for the Consolidation - Compression hazard scenario

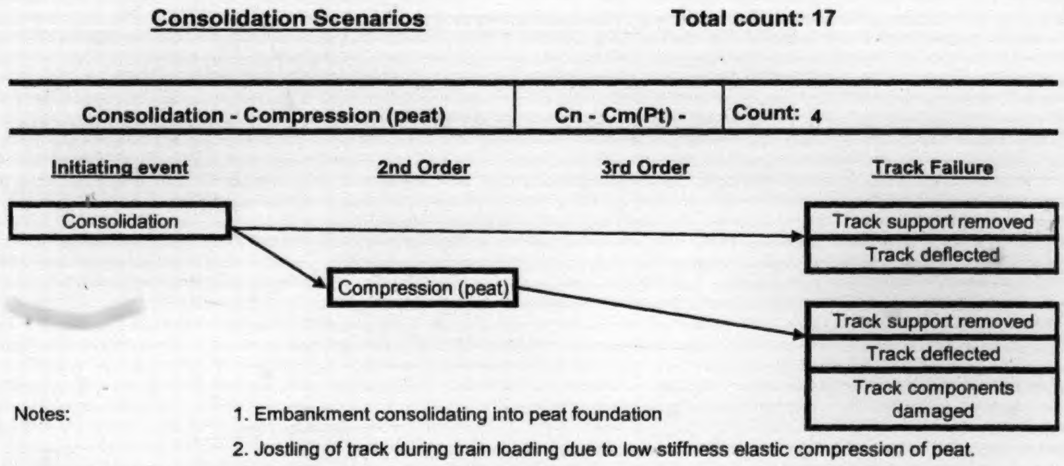

Consolidation Scenarios
Total count: 17
Consolidation - Earth (peat) Spread
Cn - E(Pt)Sp -
Count: 4
Initiating event
2nd Order
3rd Order
Track Failure
Consolidation
Earth(Peat) Spread
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. Embankment consolidating into peat foundation
2. Embankment shows distress suggesting rupture surface formed through embankment fill

Figure 9-4 Simplified FMEA for the Consolidation – Earth (peat) Spread hazard scenario

The Consolidation – Earth (peat) Spread hazard scenario is typical of earth embankment fills underlain by peat substrata. The embankment fills were usually constructed over corduroy timber mats to prevent tearing through the peat surface which has high tensile strength due to desiccation and surface vegetation. As consolidation occurs in the underlying peat the corduroy layer is subjected to higher tensile stress. Placing corduroy and the embankment should kill the peat vegetation causing embrittlement and tensile failures of the peat are more likely. If the corduroy fails the embankment fails as an earth spread into the soft peat substrata.


Consolidation Scenarios
Total count: 17
Consolidation - Compression (peat)
Cn - Cm(Pt) -
Count: 4
Initiating event
2nd Order
3rd Order
Track Failure
Consolidation
Compression (peat)
Track support removed
Track deflected
Track support removed
Track deflected
Track components damaged

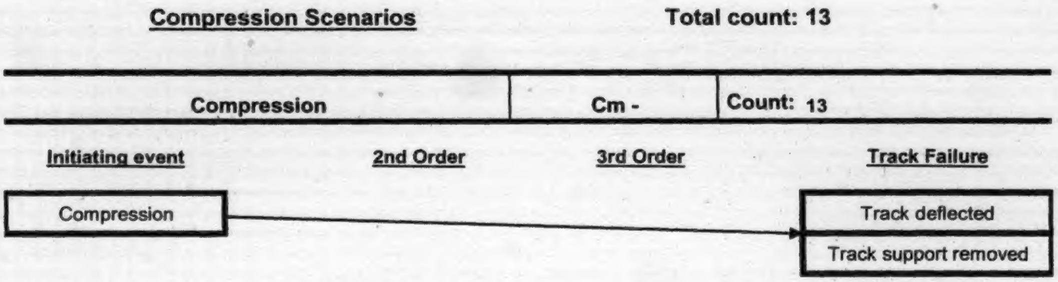
Notes: 1. Embankment consolidating into peat foundation

2. Jostling of track during train loading due to low stiffness elastic compression of peat.

Figure 9-5 Simplified FMEA for the Consolidation – Earth (peat) Spread hazard scenario

9.2.3 Compression Scenarios

Figure 9-6 depicts the simplified FMEA's for Compression hazard scenarios, the only scenario in this subgroup. Compression hazard events refer to differential compression and settlement associated with poorly compacted or dumped fills. Differential compaction occurs in fills placed by dumping with little or no mechanical stabilization through compaction or due to a thick section of ballast under one or both sides of the track. A review of these records indicates most of these sites involve circumstances where the track had actually been incrementally moved off the centerline of the embankment or was raised too high to a point where the ballast was raveling down the slope of the embankment. The lack of lateral confinement of the ballast was resulting in compression settlement in the ballast. This scenario can cause track failure by either removing support from the track structure or deflecting the track surface.


Compression Scenarios
Total count: 13
Compression
Cm -
Count: 13
Initiating event
2nd Order
3rd Order
Track Failure
Compression
Track deflected
Track support removed

Notes:

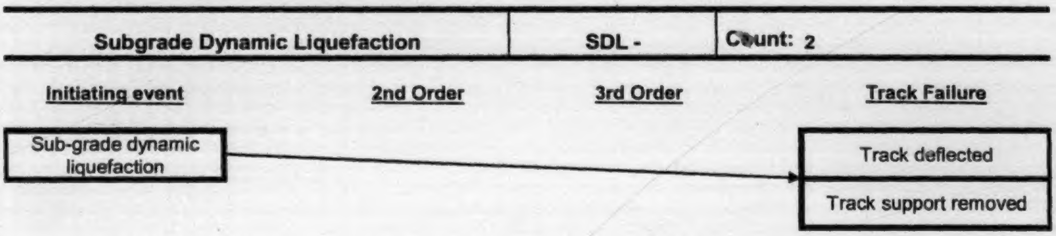
1. Cm hazard in ballast due to thick or unsupported ballast
2. Common where track aligned off embankment or ballast mounting either side of settlement

Figure 9-6 Simplified FMEA for the Compression hazard scenario.

9.2.4 Subgrade Dynamic Liquifaction Scenarios

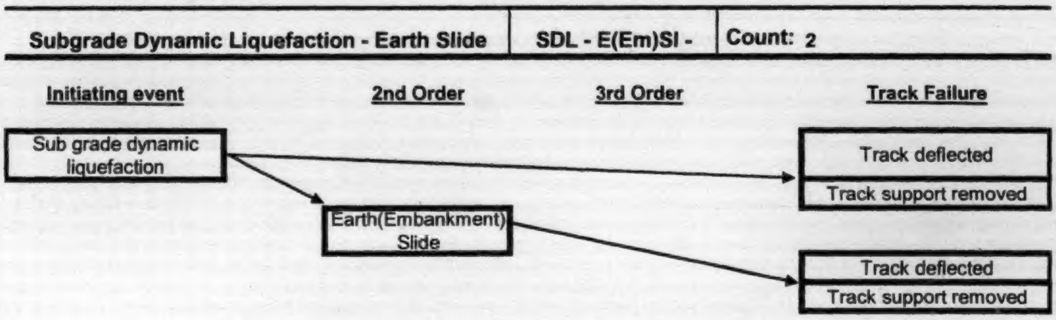
Figure 9-7 and Figure 9-8 depict the simplified FMEA for Subgrade Dynamic Liquefaction and Subgrade Dynamic Liquefaction – Earth Slide, the two hazard scenarios in this subgroup. Recall that subgrade dynamic liquefaction events involve incremental differential settlement localized to the track ballast and sub-grade which occurs in saturated fine-grained, non-cohesive soils or fouled ballast and is the result of dynamic liquefaction induced by cyclic train loading. All four of the identified hazard sites have suspected ballast troughs or pockets where water collects and saturates either the fouled ballast fines or the silty sub-grade beneath the ballast. In the case of the two Subgrade Dynamic Liquefaction – Earth Slide sites it is evident that water drains down the ballast trough out of cut sections on either side into the ballast pocket on a predominantly silt embankment. The downward moving wetting front from the water ponding in the ballast trough saturates and introduces positive pore pressures in the upper portion of the silty embankment creating a potential earth slide event. Both these scenarios can cause track failure by either removing support from the track structure or deflecting the track surface.

Subgrade Dynamic Liquefaction Scenarios **Total count: 4**


Subgrade Dynamic Liquefaction
SDL -
Count: 2
Initiating event
2nd Order
3rd Order
Track Failure
Sub-grade dynamic liquefaction
Track deflected
Track support removed

Notes: 1. Typically non-cohesive silty embankments with ballast trouves

Figure 9-7 Simplified FMEA for the Subgrade Dynamic Liquefaction hazard scenario


Subgrade Dynamic Liquefaction - Earth Slide
SDL - E(Em)Sl -
Count: 2
Initiating event
2nd Order
3rd Order
Track Failure
Sub grade dynamic liquefaction
Earth(Embankment) Slide
Track deflected
Track support removed
Track deflected
Track support removed

Notes:
1. Typically non-cohesive silty embankments with ballast trouves
2. E(Em)Sl occurs due to chronic ponding in trouve shearing extends into embankment

Figure 9-8 Simplified FMEA for the Subgrade Dynamic Liquefaction – Earth Slide hazard scenario

Note that there were no subsidence hazard scenarios identified starting with collapse hazard events.

9.3 Subsidence Hazard Scenarios Ground Conditions and Processes.

This section describes the ground conditions and processes common to subsidence hazard events. From Section 2.3 the Level III sub-grouping of subsidence hazard events is based on the rate of downward movement of the track. Settlement is a slow process and is the more common occurrence in rail grades. Collapse is a rapid occurrence usually associated with displacement into a void and, although less common, is significant due to the potential for rapid grade failure with little to no warning. The following sections provide a brief description of the Level IV subsidence hazard event subgroups.

9.3.1 Settlement: Consolidation

Consolidation involves the adjustment of a saturated soil foundation in response to increased load. It is controlled by the drainage of water from the pores and a decrease in void ratio (AGI, 1976). This occurs in soils of low permeability such as organic terrain (muskeg) and soft compressible clays where drainage and thus settlement is slow. Fills placed across this ground can settle for many years, responding to the consolidation characteristics of peat and clay soils and to compositional changes (organic decay) occurring in the foundation. Activities, such as bank widening, slope flattening and berming, change the loading condition and may re-activate the consolidation process.

9.3.2 Settlement: Compression

Compression involves a system of forces or stresses that tend to decrease the volume or shorten a substance, or the change of volume produced by such a system of forces (AGI 1976). In the context of railway ground hazards the concern typically stems from differential compression and settlement associated with poorly compacted or dumped fills or thick, unconfined ballast sections. Differential compaction occurs in fills placed by dumping with little or no mechanical stabilization through compaction. Under the applied load of trains, the weight of the overburden and loads resulting from wetting and drying, compaction occurs at differing rates resulting in irregular settlement. Heterogeneity of the fill can be a contributing factor. Such processes can remain active for many years.

The compression hazard scenarios identified all involve an excessive thickness of ballast below the tracks and the lack of shoulder width. The thick uncompactable ballast layer is in a loosely packed state subject to compression under train loading. This is commonly the result of continuous track lifting due to either consolidation of peat or an earth slideof part or all of the track sub-grade.

Even when the peat is fully consolidated the sub-grades tend to be relatively spongy. That is, the peat behaves as a low stiffness elastic material which deflects after each wheel loading. The resulting ground surface wave action in front of each wheel set causes the ties to move in a circular fashion resulting in heavy wear on ties and track fastening and bearing components. Figure 9-9 depicting damaged track components from this type of compression hazard event at Mile 101.9 of CN's Edson Subdivision.

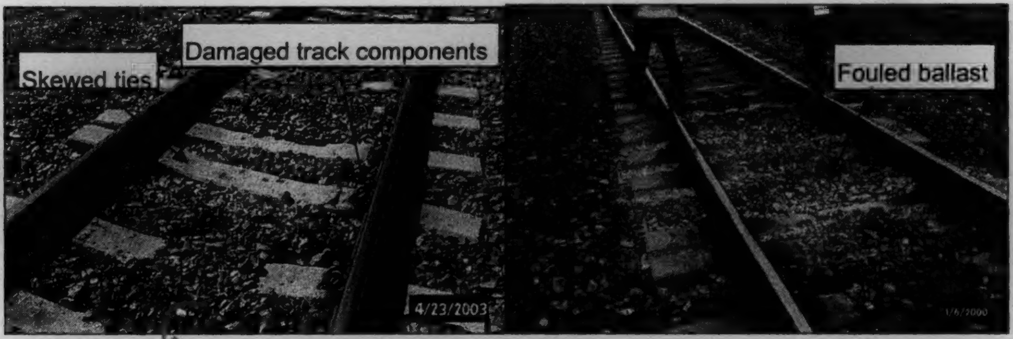


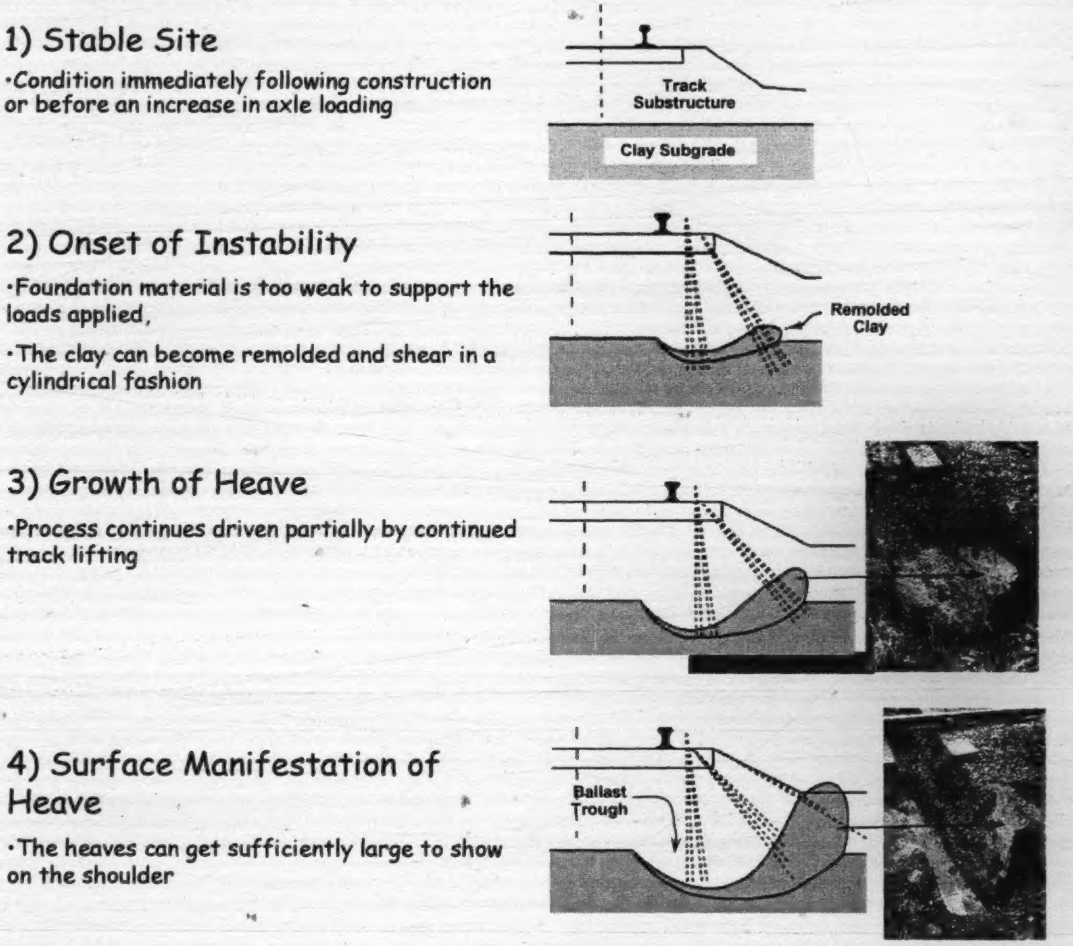
Figure 9-9 Skewed ties, fouled ballast and damaged track components the result of a Consolidation – Compression (peat) scenario event at Mile 101.9 CN's Edson Subdivision (photos by Tim Keegan, CN file 4670-EDS-101.9-102.1)

9.3.3 Settlement: Sub-grade Plastic Deformation (SPD)

Referred to as progressive shear failure by Selig (1994), subgrade plastic deformation occurs when repetitive loads cause local over-stressing and incremental plastic deformations of fine-grained soils with low angles of shearing resistance common to clay sub-grades. Plastic deformation occurs at the top of the sub-grade where the loads are highest. It begins with the squeezing out of the sub-grade from beneath the tracks giving rise to depressions. Degradation of soil strength due to water collecting in depressions accelerates the plastic deformations. Breakage of ties at the 1/3-point is common in areas showing severe plastic deformations.

Almost without exception a low shear strength cohesive subgrade is the preparatory causal factor for subgrade plastic deformation. The process is similar to bearing capacity failure in that the static and dynamic loading from a train incrementally exceeds the shear strength of the weaker clay subgrade. As shown in Figure 9-10, the incremental process of plastic deformation starts gradually, brought on by insufficient track soil strength, ballast and subballast, or an increase in train loading. It accelerates, as shown in Figure 9-10, 3), as the clay strain softens and drainage is impeded by the formation of the clay ridge. Track maintenance forces are required to lift the track to maintain a safe running surface. This cycle of settlement and lifting serves to accelerate the failure process. This process ultimately results in the formation of a ballast trough (Figure 9-10, 4). The appearance and characteristics of a ballast trough are presented in Figure 9-11

Figure 9-12 illustrates the appearance of a subgrade plastic deformation event in the later stages of development at Mile 67.6 of CN's Edson Subdivision in June, 2002. The subgrade material is a CI to CH clay and this section of track is on a through cut approach onto a bridge. The SPD event initiated following subcutting and lowering of the track by approximately 150 mm. It is inferred that the removal of 150mm of structural fill (ballast) was sufficient to increase the stresses such that they exceeded the weak subgrade strength.



1) Stable Site

- Condition immediately following construction or before an increase in axle loading

2) Onset of Instability

- Foundation material is too weak to support the loads applied,
- The clay can become remolded and shear in a cylindrical fashion

3) Growth of Heave

- Process continues driven partially by continued track lifting

4) Surface Manifestation of Heave

- The heaves can get sufficiently large to show on the shoulder

Track Substructure
Clay Subgrade
Remolded Clay
Ballast Trough

Figure 9-10 Illustration of a subgrade plastic deformation process (modified from Selig and Waters, 1994).

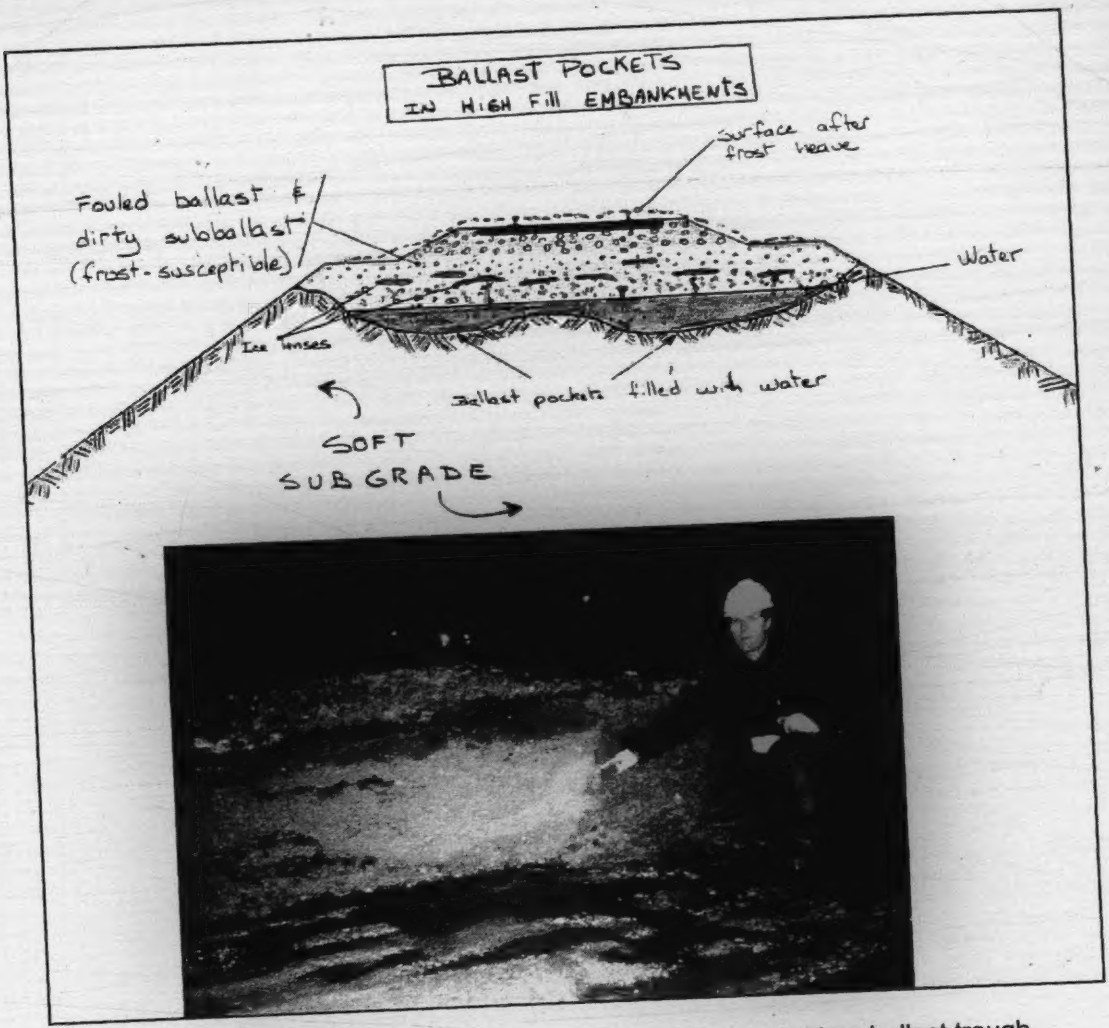

BALLAST POCKETS
IN HIGH FILL EMBANKMENTS
Surface after frost heave
Fouled ballast & dirty subballast (frost-susceptible)
Water
Ice lenses
Ballast pockets filled with water
SOFT SUBGRADE

Figure 9-11 Sketch section and photo of an SPD that resulted in a ballast trough (Sketch and photo courtesy of Mario Ruel, CN Senior Geotechnical Engineer, Montreal)

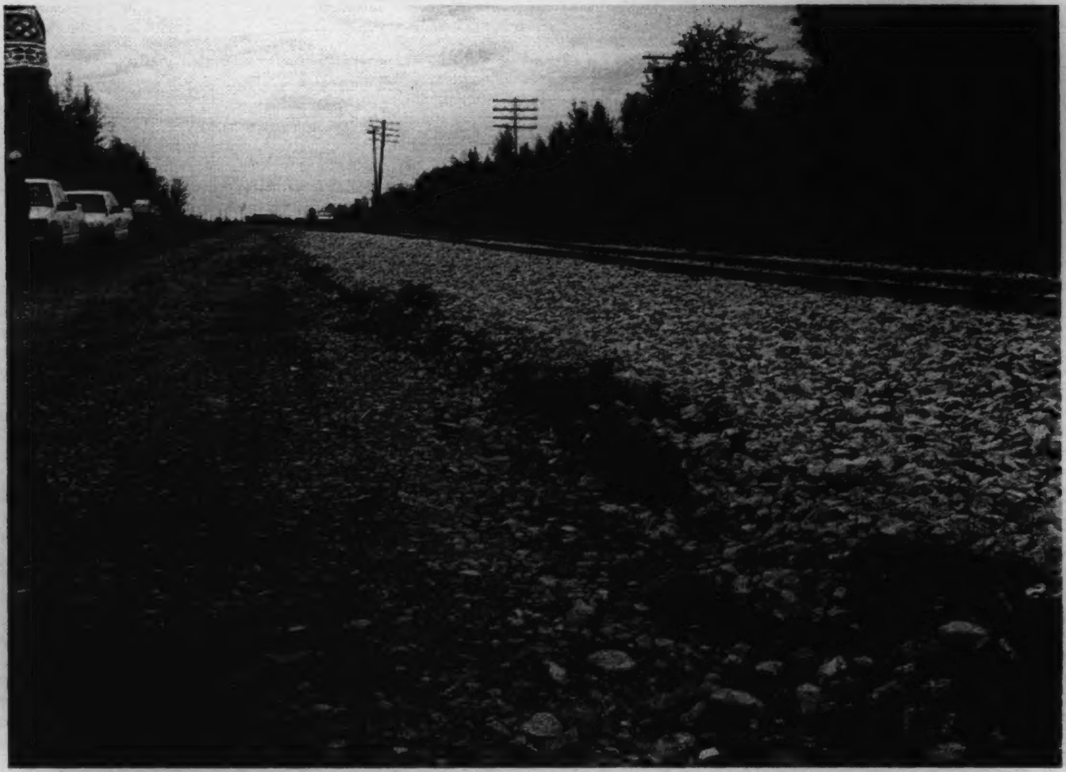
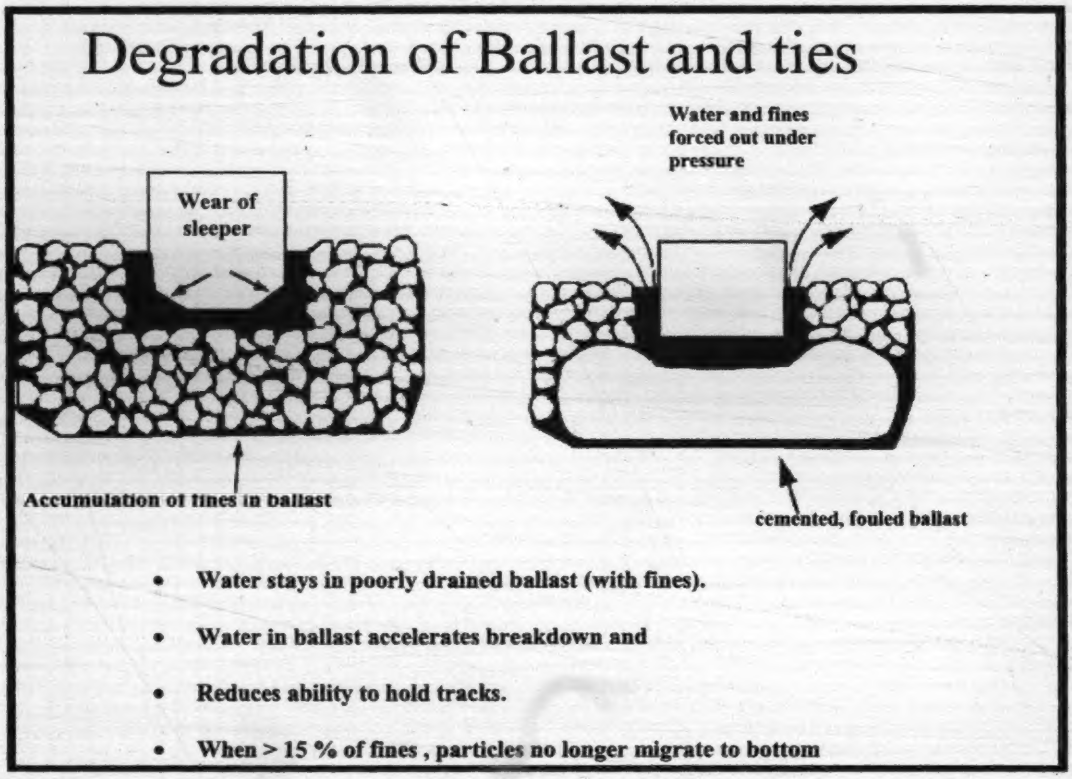


Figure 9-12 Illustration of a mud ridge and settlement caused by a subgrade plastic deformation event at Mile 67.6 CN's Edson Subdivision near Evansburg, Alberta (photo by Tim Keegan taken June 27, 2002, CN file ref 4670-EDS-67.6).

9.3.4 Settlement: Subgrade Dynamic Liquefaction (SDL)

These subgrade dynamic liquefaction (SDL) hazards require saturated silt produced from the abrasion of ballast particles or from the existing subgrade to exist. Once these preparatory conditions exist the dynamic loading of the train wheels induce a build up of excess pore pressures and reduction of shear strength in the subgrade. Although liquefaction likely does not occur, the resulting minor shear strains appear to occur incrementally and, over time, can cause track failure by track deflection. The process leads to further abrasion and production of additional silt from the ballast, the formation of ballast troughs and ultimately the formation of what are termed mud spots by railway personnel, as the saturated fines build up to the surface of the ballast. Figure 9-13 illustrates a sub-grade dynamic liquefaction event occurring principally in the ballast section.

Of note is that fine non-cohesive soils are frost susceptible. So, frost heaves are often associated with subgrade dynamic liquefaction. As a frost heave thaws from the surface downwards, a layer of saturated fines is trapped just below the ballast which often results in subgrade dynamic liquefaction.


Degradation of Ballast and ties
Wear of sleeper
Water and fines forced out under pressure
Accumulation of fines in ballast
cemented, fouled ballast

- **Water stays in poorly drained ballast (with fines).**
- **Water in ballast accelerates breakdown and**
- **Reduces ability to hold tracks.**
- **When > 15 % of fines , particles no longer migrate to bottom**

Figure 9-13 Illustration of sub-grade dynamic liquefaction occurring principally in the ballast section (modified from Selig and Waters, 1994)

Figure 9-14 illustrates a case example of a subgrade dynamic liquefaction event which developed over a period of months at Mile 135.22 of CN's Redditt Subdivision in northern Ontario during the spring of 2004. It is inferred that lack of drainage in the through rock cut approach to the tunnel was a preparatory causal factor for this hazard scenario.

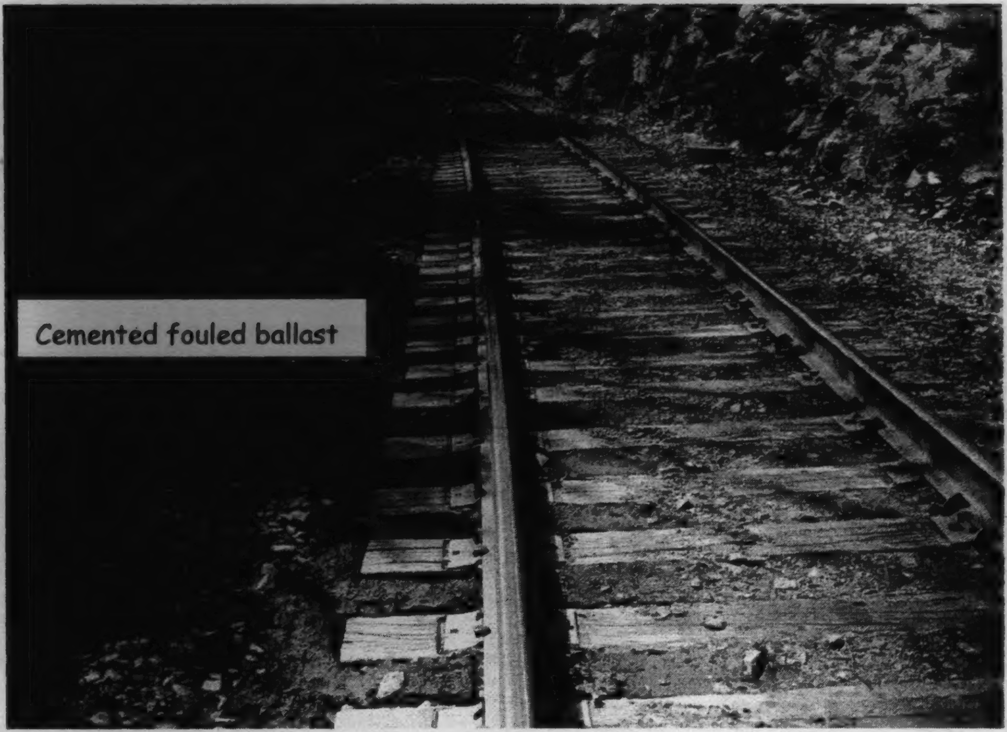


Figure 9-14 Case example of a subgrade dynamic liquefaction event at Mile 135.22 of CN's Redditt Subdivision (Photo by Tim Keegan, taken April 27, 2004 CN file 4670-RDT-135.22)

9.3.5 Collapse: Piping

Collapses into voids form as the results of seepage and piping. These may develop quickly in permeable soils where voids form. The volume of collapse resulting from these processes depends on the soil's ability to maintain an arched opening, the soil's chemical makeup and on the erodibility of the material. A case example of this type of collapse hazard event is provided by the injury derailment which occurred at Mile 89.7 of CN's Kinghorn Subdivision near Orient Bay, Ontario in 1994 (TSB, 1996). Subsequent investigation of the incident revealed piping cavities in the surrounding non-cohesive, lightly-cemented, calcareous, lacustrine silt. Although the track failure was attributed to seepage and piping erosion following a snow melt, the propensity for the piping voids to stay open in the calcareous, cemented silt was identified as a significant preparatory cause for the event. Figure 9-15 provides a photo of the Orient Bay derailment.

Figure 9-15 Photo of the Orient Bay Derailment Mile 89.7 of CN's Kinghorn Subdivision date April 25, 1994 (CN ref, 4670-KGH-89.7).

9.3.6 Collapse:Dissolution

This involves collapse into voids in rock developed by solution generally in limestone, dolomite or gypsum. This is commonly associated with karst topography which is not known to exist along CN's tracks in Western Canada.

9.3.7 Collapse:Culvert failure

This involves collapse into a void caused by a failed culvert. Culverts can fail due to corrosion or physical damage such as a pull-apart at a joint. The culvert either collapses into itself or a void is formed outside of the culvert when soil trickles in from the top, is sucked in from the bottom by negative pressure from flowing water or is removed through erosion by water flowing outside of the culvert.

Culvert failure hazard events are included in the most common overland / through flow erosion hazard scenario namely Seepage Erosion / Piping / Gully Erosion- Earth Slide / Culvert Failure / Piping Void Collapse presented in Chapter 11. In these scenarios the structural integrity of the culvert has been observed or is likely to be compromised by either high flows, an earth (embankment) slide in the ground around the culvert or by a seepage erosion and piping around the culvert.

A review of these records reveals that in most culvert collapse hazards the culvert was compromised structurally either by corrosion, abrasion, an earth slide, settlement, overloading or buoyant jacking at its inlet due to excessive surcharging of the culvert. The collapse hazard results from either the culvert collapsing or from voids being formed around the culvert when material trickles into the culvert or is sucked in by flowing water through an opening in the damaged culvert. The prevalent trigger causal factors identified for culvert failure hazard scenarios include intense rain which will cause high flows or surcharging of the culvert, significant antecedent rain which results in sustained flows through the culvert and snow melt.

9.3.8 Collapse:Timber deterioration

This involves collapse into voids formed by rotting buried timber structures such as trestles, corduroy or abandoned timber box culverts common to railway fills.

9.3.9 Collapse:Voids in rock fill

This involves collapse into voids inherent in large uniform graded rock fill embankments.

9.3.10 Collapse:Liquefaction

This involves collapse into underlying liquefied soils. Most likely triggered by cyclic earthquake loading.

9.3.11 Collapse:Burrowing Animals

This involves collapse into voids formed in the sub grade by burrowing animals such as beavers, groundhogs and bears.

9.3.12 Collapse:Utilities

This involves collapse into voids formed under the sub grade by pipe utilities either from installation or from leakage of product and erosopn of the surrounding ground.

9.3.13 Collapse:Mining

This involves collapse into voids formed under the sub grade by new, existing or abandoned mining works.

9.4 Settlement Hazard Scenarios Rates of Ground Hazard System Failure

Table 6-2 presents a summary of the subjectively estimated rates of track failure the author have recorded for the CN Western Canada subsidence hazard scenarios. By definition the processes of settlement are slow or incremental over time and this is reflected in the majority of the scenarios identified. The reason for the estimation of rapid track failure recorded for some of the Subgrade Plastic Deformation, Consolidation – Compression, Consolidation - Earth (peat) Spread, Consolidation – Compression (peat), Compression and Subgrade Dynamic Liquefaction scenarios is my concern that track failure could or had occurred during incremental train loading and the track failure occurs rapidly as the train passes the site. Recall that track failure occurs when the track becomes unsafe for train loading at track speed and this may occur as the train passes over the site.

Table 9-2 Estimated rates of tracks failure recorded for subsidence hazard scenarios.

					Percentage of Ground Hazards Reporting this Speed				
Level II Groups	**Level III Subgroups**	**Ground Hazard Scenario**	**Coding**	**Count**	**Very Rapid**	**Rapid**	**Moderate**	**Slow**	**Very Slow**
Subsidence	*Settlement*	**Subgrade Plastic Deformation**							
		Subgrade Plastic Deformation	SPD -	13	0%	23%	8%	62%	0%
		Subgrade Plastic Deformation - Earth Slide	SPD - E(Em)Sl -	7	0%	0%	29%	71%	0%
			Subtotal	**20**	**0%**	**15%**	**15%**	**65%**	**0%**
		Consolidation							
		Consolidation - Compression	Cn - Cm -	9	0%	44%	11%	11%	22%
		Consolidation - Earth Spread	Cn - E(Pt)Sp -	4	25%	25%	0%	50%	0%
		Consolidation - Compression (peat)	Cn - Cm(Pt) -	4	0%	25%	0%	50%	0%
			Subtotal	**17**	**6%**	**35%**	**6%**	**29%**	**12%**
		Compression							
		Compression	Cm -	13	0%	23%	23%	23%	0%
			Subtotal	**13**	**0%**	**23%**	**23%**	**23%**	**0%**
		Subgrade Dynamic Liquifaction							
		Subgrade Dynamic Liquifaction	SDL -	2	0%	100%	0%	0%	0%
		Subgrade Dynamic Liquifaction - Earth Slide	SDL - ESl -	2	0%	0%	0%	100%	0%
			Subtotal	**4**	**0%**	**50%**	**0%**	**50%**	**0%**
	Total Subsidence Scenario Hazards			**54**	**2%**	**26%**	**13%**	**43%**	**4%**

Table 9-3 provides my suggested timing and lag time characteristics for the eight subsidence hazard scenarios.

Table 9-3 Suggested timing and estimated time lag for each subsidence scenario.

Subsidence Scenario	Timing of Individual event	Lag Time Between Events
SPD -	• Incremental with train loading	NA
SPD - E(Em)Sl -	• Both - Incremental with train loading • E(Em)Sl - Following significant antecedent rain or snow melt	• Weeks to years
Cn - Cm -	• Cn – Continuous but diminishing with surcharge and incremental with train loading • Cm - Incremental with train loading	• Months to years
Cn - E(Pt)Sp -	• Cn – Continuous but diminishing with surcharge and incremental with train loading • E(Pt)Sp - Following significant antecedent rain or following exposure of the corduroy base to aerobic conditions	• Years to decades
Cn - Cm(Pt) -	• Cn – Continuous but diminishing with surcharge and incremental with train loading • Cm(Pt) - Incremental with train loading	• Months to years
Cm -	• Cm – Diminishing following surcharge and incremental with train loading	• N/A
SDL -	• Incremental with train loading	• N/A
SDL - ESl -	• SDL - Incremental with train loading • ESl - Following significant antecedent rain, intense rain or snow melt	• Months to years

9.5 Subsidence Hazard Scenarios Track Stability States.

Because railway track maintenance forces periodically inspect and, as required, lift and line the track surface and settlement by definition occurs slowly or incrementally, these scenarios usually remain in the (3) *Stable – monitoring required* track stability state. These scenarios would be elevated to a (2) *Marginally Stable* state if conditions worsen so that a trigger causal factor, such as a single train passage, can cause track failure. The other changes that would elevate the track stability state to (2) *Marginally Stable* would be a shift in any one of the second order hazard stages to *Marginal* or *Suspended*.

Collapse hazards, such as voids beneath the track would move the track into a marginal stable state as trigger causal factors, primarily train loading, would be assessed upon discovery. The track stability state for liquefaction collapse hazards would require assessment of the vulnerability of the hazard scenario to the trigger causal factor, primarily the likelihood and magnitude of seismic loading.

9.6 Subsidence Hazard Scenarios Preparatory Causal Factors

9.6.1 Observed Subsidence Preparatory Causal Factors

Error! Reference source not found. presents the preparatory causal factors identified for each subsidence hazard scenario. The following sections discuss the preparatory causal factors for subsidence indicated on the geotechnical inspection form by the author for each subsidence scenario subgroups.

9.6.1.1 Subgrade Plastic Deformation Scenarios

There are no significant preparatory causal factors recorded for Subgrade Plastic Deformation (SPD) Scenarios in **Error! Reference source not found.**. However, as indicated earlier, almost without exception a low shear strength cohesive subgrade is the preparatory causal factor for SPD. As well, increased train loading, poor drainage, presence of a ballast trough and reduction of the structural fill section (ballast and sub-ballast) are observed by the author to be preparatory causal factors.

9.6.1.2 Consolidation Scenarios

The main preparatory causal factors indicated for Consolidation hazard scenarios in **Error! Reference source not found.** include ponding or high water tables, plugged or non-existent ditches. Although not specifically indicated on **Error! Reference source not found.** , the records reveal that the preparatory causal factor for consolidation is the presence of peat or a highly organic sub-stratum. As peat bogs form in topographic lows these sites commonly have poorly drained conditions as a secondary preparatory causal factor. When the terrain has frequent bedrock knobs, the consolidation hazard is accentuated where the track transitions on or off of bedrock.

The Author has observed, that much of the CN railway grade in Canada built over peat areas, was placed over crisscrossed or parallel placed tree trunks called corduroy. The function of the tree trunk was to transform, the point load beneath the rail, into a line load carried across the width of the fill. This redistribution of stresses resists bearing capacity failure of the peat foundation and differential settlement of the fill. In most cases, the corduroy was pushed down below the water table into an anaerobic environment where rot is slowed down. However, a drop of the water table, due to either drought conditions, or a revision to drainage conditions, which exposes the peat to aerobic or drying conditions, can be a preparatory causal factor for additional consolidation or sudden embankment failure (earth spread) due to disintegration and weakening of the corduroy by rot.

9.6.1.3 Compression Scenarios

The records indicate that all of the identified compression hazards are the result of compression of the ballast directly below the ties due to insufficient lateral support for the ballast layer. The incremental settlement of the track driven by train loading is the result of looser packing of the open, uniform graded ballast and a lateral bulging of the ballast due to the lack of lateral constraint. The preparatory causal factors for these hazard scenarios include the track being moved to the crest of the embankment top surface, allowing ballast to ravel off the embankment crest, and the track being incrementally lifted too high, resulting in the ballast layer being too thick.

9.6.1.4 Subgrade Dynamic Liquifaction Scenarios

The commonly associated preparatory causal factors for Subgrade Dynamic Liquefaction scenarios include silty subgrades, ballast at the end of its design life, ballast pockets, high impact locations (such as joints, bridge abutments, switches, diamonds or crossing), ponding water and an elevated phreatic surface, poor drainage and the thawing of ice lenses at frost heave locations.

Level III Subgroups	Ground Hazard Scenario	Coding	Count	Erosion	Poor Drainage	Beaver Activity	Other Observations
Settlement	**Subgrade Plastic Deformation**						
	Subgrade Plastic Deformation	SPD -	13				Shoulder Sloughing(15%),Ballast Sloughing(15%),
	Subgrade Plastic Deformation - Earth (embankment) Slide	SPD - E(Em)Sl -	7	Piping (14%),	Partially(14%),Poor Inlet(14%),	Active(14%),Habitat(14%),	Shoulder Sloughing(14%),Ballast Sloughing(29%),
		Subtotal	20	Piping (5%),	Partially(5%),Poor Inlet(5%),	Active(5%),Habitat(5%),	Shoulder Sloughing(15%),Ballast Sloughing(20%),
	Consolidation						
	Consolidation - Compression	Cn - Cm -	9		Blocked(11%),	Active(11%),Habitat(11%),	Shoulder Sloughing(22%),Ballast Sloughing(33%),
	Consolidation - Earth (peat) Spread	Cn - E(Pt)Sp -	4				Shoulder Sloughing(50%),Ballast Sloughing(50%),
	Consolidation - Compression (peat)	Cn - Cm(Pt) -	4		Ponding or HWT(25%),Marshes(50%),Plugged Ditches(50%),	Active(50%),Habitat(50%),	
		Subtotal	17		Blocked(6%),Ponding or HWT(6%),Marshes(12%),Plugged Ditches(12%),	Active(18%),Habitat(18%),	Shoulder Sloughing(24%),Ballast Sloughing(29%),
	Compression						
	Compression	Cm -	13	Slope (54%),Seepage (15%),Stream (8%),River(8%),			Shoulder Sloughing(54%),Ballast Sloughing(54%),Damaged Structure(8%),
		Subtotal	13	Slope (54%),Seepage (15%),Stream (8%),River(8%),			Shoulder Sloughing(54%),Ballast Sloughing(54%),Damaged Structure(8%),
	Subgrade Dynamic Liquifaction						
	Subgrade Dynamic Liquifaction	SDL -	2		Ponding or HWT(50%),Marshes(50%),Plugged Ditches(50%),		Shoulder Sloughing(50%),Ballast Sloughing(50%),
	Subgrade Dynamic Liquifaction - Earth Slide	SDL - ESl -	2				Shoulder Sloughing(50%),
		Subtotal	4				
Total Subsidence Scenario Hazards			54	Piping (2%), Slope (13%),Seepage (4%),Stream (2%),River(2%),	Partially(2%),Blocked(2%),Poor Inlet(2%),Ponding or HWT(2%),Marshes(4%),Plugged Ditches(4%),	Active(7%),Habitat(7%),	Shoulder Sloughing(28%),Ballast Sloughing(30%),Damaged Structure(2%),

Table 9-4 Preparatory causal factors identified for each settlement hazard scenario grouped into erosion, poor drainage, beaver activity and other observations. The percentage each preparatory causal factor was reported for each hazard scenario is presented in brackets.

9.6.2 Suggested Settlement Hazard Preparatory Causal Factors

Settlement hazards are named after the ground condition or process that cause them and thus the name given to the settlement hazard becomes one of the causal factors. The author's suggested list and descriptions of railway settlement hazard preparatory causal factors are presented in Table 9-5.

Table 9-5 Preliminary railway settlement hazard preparatory causal factors

Preparatory Causal Factors – Settlement		**Description**
1.Ground Conditions		
PS	Peat sub-grade	Hazard enhanced if settlement is irregular or differential or the deposit is deep or has a high moisture content > 500%. and to compositional changes (organic decay) occurring in the foundation.
SNCC	Soft, normally consolidated clay sub-grade	Prerequisite for settlement hazards resulting from time dependent consolidation of clay. Fills placed across this ground can settle for many years, responding to the consolidation characteristics of the clay.
PC/DF	Poorly compacted or dumped fills	Differential compression and settlement associated with poorly compacted or dumped fills (placed very dry, very wet or on compressible subgrades such as muskeg). Differential compaction occurs in fills placed by dumping with little or no mechanical stabilization through compaction. Heterogeneity of the fill can be a contributing factor.
WC	Weak clay sub-grades	Presence of weak clay sub-grades can cause incremental plastic deformation and settlement of the track from repetitive train loads.
FNS/FB	Fine-grained, non-cohesive soils/ fouled ballast	Presence of fine-grained non-cohesive sub-grade soils or fouled ballast can cause incremental differential settlement of the track induced by cyclic train loading. More common in ballast at the end of its design life, ballast pockets, high impact locations (such as joints, bridge approaches, switches, diamonds or crossing), and at frost heave locations.
LS	Liquefiable soils	Presence of contractive silty soils susceptible to either cyclic train loading or cyclic seismic loading when saturated.
2.Geomorphological Processes		
FH	Frost Heaves	Subgrade dynamic liquefaction is common during thaw of ice lenses at frost heave locations.
3.Physical Processes		

Preparatory Causal Factors – Settlement		**Description**
LLISM	Low level Intense snow melt	Provides rapid recharge of water into the ballast trough reducing effective stress and shear strength in fouled ballast, sub-ballast or sub-grade.
SAR	Significant antecedent rainfall	Causes an abundance of free water saturating the ballast trough reducing effective stress and shear strength in fouled ballast, sub-ballast or sub-grade. Prolonged soaking will soften clay sub-grades or saturate previously unsaturated silty sub-grades weakening the sub-grade for incremental failure under train loading.
IR	Intense rainfall	Provides rapid recharge of water into the ballast trough reducing effective stress and shear strength in fouled ballast, sub-ballast or sub-grade.
HGR	High groundwater recharge	Causes a build up of water pressures and a rise in the phreatic surface below the tracks. Prolonged artesian recharge will soften clay sub-grades or saturate previously unsaturated silty sub-grades weakening the sub-grade for incremental failure under train loading.
T	Thawing	Downward thawing of the sub-grade results in perched aquifers directly below the track, which can soften clay sub-grades or saturate previously unsaturated silty sub-grades weakening the sub-grade for incremental failure under train loading. Process is particularly hazardous when ice lenses thaw after a frost heave.
Cn	Consolidation	The adjustment of a saturated soil foundation in response to increased load. Involves the squeezing of water from the pores and a decrease in void ratio. (AGI, 1976). This class refers to soils of low permeability such as organic terrain (muskeg) and soft compressible clays where drainage and thus settlement is slow. Fills placed across this ground can settle for many years, responding to the consolidation characteristics of organic or clay soils and to compositional changes (organic decay) occurring in the foundation.
Cm	Compression	Under the applied load of trains, the weight of the overburden and loads resulting from wetting and drying, compaction occurs at differing rates resulting in irregular settlement. Such processes can remain active for many years.

Preparatory Causal Factors – Settlement		**Description**
SPD	Sub-grade plastic deformation	Incremental plastic deformation and settlement of the track resulting from local over-stressing and incremental plastic deformations of clay sub-grades from repetitive train loads. Plastic deformation occurs at the top of the sub-grade where the loads are highest. It begins with the squeezing out of the sub-grade from beneath the tracks giving rise to depressions. Degradation of soil strength due to water collecting in depressions accelerates the plastic deformations.
SDL	Sub-grade dynamic liquifaction	Incremental differential settlement localized to the track ballast and sub-grade, occurs in saturated fine-grained non-cohesive soils or fouled ballast and is the result of dynamic liquefaction induced by cyclic train loading. Process leads to additional ballast fouling, formation of ballast pockets and ultimately the formation of mud spots. Commonly associated with ballast at the end of its design life, ballast pockets, high impact locations (such as joints, bridge approaches, switches, diamonds or crossing), and the thawing of ice lenses at frost heave locations.
4.Man-made or Animal Processes		
TA	Train Action	Repetitive train loads causes Incremental subgrade plastic deformation and dynamic liquefaction of the subgrade resulting in track settlement.
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can cause a rise in the phreatic surface under the tracks resulting in soften clay subgrades or saturation of previously unsaturated silty subgrades weakening the subgrade for incremental failure under train loading.

9.6.3 Suggested Collapse Hazard Preparatory Causal Factors

Similar to settlement hazard causal factors, collapse hazards are named after the ground condition or process that cause them and thus the name given to the collapse hazard becomes one of the causal factors. The suggested list and descriptions of railway collapse hazard preparatory hazards is presented in **Table 9-6**.

Table 9-6 Preliminary railway collapse hazard preparatory causal factors.

Preparatory Causal Factors - Collapse		Description
1.Ground Conditions		
PS	Peat sub-grade	Presence of peat below a track fill embankment predisposes the track to collapse of the fill into the peat substrata. May also be referred to as an earth spread failure.
VRF	Voids in rock fill	Collapse into voids inherent in large uniform graded rock fill embankments.
TS	Timber in sub-grade	Presence of timber within the soil structure supporting the track, such as trestles, corduroy or abandoned timber box culverts common to railway fills, predisposes the track to a timber deterioration hazard.
PSS	Piping-susceptible soil	The soil properties have to be such that piping can occur and the voids have propensity to remain open under the track structure.
DSS	Dissolution-susceptible rock	The rock properties have to be such that dissolution can occur and the voids have propensity to remain open under the track structure. (limestone, dolomite or gypsum. Associated with karst topography).
CSS	Collapsing soils	Soil exists in the subgrade that is susceptible to a large and sudden reduction in volume upon wetting.
LS	Liquefiable soils	Presence of contractive silty soils susceptible to either cyclic train loading or cyclic seismic loading when saturated predisposes the track to collapse due to liquefaction.
2.Geomorphological Processes		
P	Piping	Processes exist by which voids are formed by piping. Collapse hazard exists due to remnant voids formed as the result of piping in soils.
D	Dissolution	Processes exist by which voids are formed by dissolution. Collapse hazard exists due to remnant voids formed as the result of dissolution in rock.
TD	Timber deterioration	Processes exist by which voids are formed by rotting buried timber structures such as trestles, corduroy or abandoned timber box culverts common to railway fills.
3.Physical Processes		
HGR	High groundwater recharge	Causes a build up of water pressures and a rise in the phreatic surface saturating liquefiable soils below the tracks increasing the liquefaction hazard.

Preparatory Causal Factors - Collapse		Description
CF	Culvert failure	Processes exist by which culverts can be brought closer to collapse failure such as corrosion or physical damage (i.e. pull-apart at a joint). The culvert either collapses into itself or the collapse hazard is created when voids form outside of the culvert when soil trickles in from the top, is sucked in from the bottom by negative pressure from flowing water or is removed through erosion by water flowing outside of the culvert.
4.Man-made or Animal Processes		
TA	Train Action	Dynamic trainloads trigger a collapse track failure by over stressing a pre-existing void or by dynamic liquefaction of liquefiable soils beneath the track.
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can cause a rise in the phreatic surface under the tracks resulting in soften clay subgrades or saturation of previously unsaturated silty subgrades weakening the subgrade for incremental failure under train loading.
BA	Burrowing Animals	Processes and circumstances exist by which voids can be formed by burrowing animals such as beavers, bears or ground hogs in or around the track grade causing a burrowing animal collapse hazard to exist.
Ut	Utilities	Processes and circumstances exist by which voids can be formed by leaking utilities such as water, sewer or petroleum product pipelines in or around the track grade causing a utility collapse hazard to exist.
M	Mining	Processes and circumstances exist by which voids can be formed by active or abandoned mining operations in or around the track grade causing a mining collapse hazard to exist.

9.6.4 Observed Settlement Hazard Scenario Trigger Causal Factors

Error! Reference source not found. presents the trigger causal factors identified for each settlement hazard scenario.

Table **9-8** provides a summary of the most prevalent trigger causal factors identified in **Error! Reference source not found.**. Track failure from a settlement hazard is most commonly a deflection of the track both vertically and horizontally such that a rail car can not pass over the misalignment at track speed without derailing. The trigger causal factors identified here are considered sufficient to directly cause such a deflection. Most if not all of these trigger causal factors need to occur in combination with train action to cause the necessary deflection.

9.6.4.1 Subgrade Plastic Deformation Scenarios

The prevalent trigger causal factors identified for subgrade plastic deformation scenarios are intense rain, an elevated phreatic surface immediately under the tracks, snow melt, and train action. Train action is the most critical trigger as this implies the train is occupying the track when it fails.

9.6.4.2 Consolidation Scenarios

The prevalent trigger causal factors identified for consolidation scenarios are intense rain, an elevated phreatic surface in the peat, snow melt or frost thawing at the surface of the peat each in combination with train action.

9.6.4.3 Compression Scenarios

The prevalent trigger causal factors identified for compression scenarios are intense rain an elevated phreatic surface in the peat, snow melt or frost thawing at the surface of the peat each in combination with train action.

9.6.4.4 Subgrade Dynamic Liquefaction Scenarios

The prevalent trigger causal factors identified for subgrade dynamic liquefaction hazard scenarios include significant antecedent rain, snow melt, frost thaw from a frost heave all in combination with train action.

Level II Groups	Level III Subgroups	Ground Hazard Scenario	Coding	Count	Intense Rain	Prolonged Rain	High Water	High Water Table	Piping	Freeze/Thaw	Snow Melt	Raising Freezing Level	Rapid Drawdown	Heavy Snow	Thaw	Anthropogenic	Train Action
Subsidence	*Settlement*	**Subgrade Plastic Deformation**															
		Subgrade Plastic Deformation	SPD -	13	69%	69%	0%	15%	0%	0%	62%	0%	0%	0%	31%	0%	92%
		Subgrade Plastic Deformation - Earth Slide	SPD - E(Em)Sl -	7	100%	100%	0%	0%	0%	0%	86%	0%	0%	0%	0%	0%	100%
			Subtotal	**20**	**80%**	**80%**	**0%**	**10%**	**0%**	**0%**	**70%**	**0%**	**0%**	**0%**	**20%**	**0%**	**95%**
		Consolidation															
		Consolidation - Compression	Cn - Cm -	9	22%	22%	11%	44%	0%	11%	56%	0%	0%	0%	67%	0%	11%
		Consolidation - Earth (peat) Spread	Cn - E(Pt)Sp -	4	25%	50%	0%	50%	0%	0%	75%	0%	0%	0%	25%	0%	50%
		Consolidation - Compression (peat)	Cn - Cm(Pt) -	4	50%	75%	25%	75%	0%	50%	50%	0%	0%	0%	50%	0%	25%
			Subtotal	**17**	**29%**	**41%**	**12%**	**53%**	**0%**	**18%**	**59%**	**0%**	**0%**	**0%**	**53%**	**0%**	**24%**
		Compression															
		Compression	Cm -	13	54%	38%	8%	31%	0%	15%	46%	0%	8%	0%	38%	0%	38%
			Subtotal	**13**	**54%**	**38%**	**8%**	**31%**	**0%**	**15%**	**46%**	**0%**	**8%**	**0%**	**38%**	**0%**	**38%**
		Subgrade Dynamic Liquifaction															
		Subgrade Dynamic Liquifaction	SDL -	2	0%	100%	50%	0%	0%	50%	50%	0%	0%	0%	100%	0%	100%
		Subgrade Dynamic Liquifaction - Earth Slide	SDL - ESl -	2	50%	50%	50%	50%	0%	0%	0%	0%	0%	0%	0%	0%	100%
			Subtotal	**4**	**25%**	**75%**	**50%**	**25%**	**0%**	**25%**	**25%**	**0%**	**0%**	**0%**	**50%**	**0%**	**100%**
		Total Subsidence Scenario Hazards		**54**	**54%**	**57%**	**9%**	**30%**	**0%**	**11%**	**57%**	**0%**	**2%**	**0%**	**37%**	**0%**	**59%**

Table 9-7 Trigger causal factors identified for each settlement hazard scenario identified. The percentage each trigger causal factor was reported for each hazard scenario and each hazard scenario subgroup is presented.

Table 9-8 Summary of prevalent settlement hazard trigger causal factors identified according to the settlement hazard scenario

Settlement Hazard Scenarios	Prevalent Trigger Causal Factors Identified	
Subgrade Plastic Deformation	• Intense rain • Significant antecedent rain	• Snow melt • Train action
Subgrade Plastic Deformation - Earth Slide	• Intense rain • Significant antecedent rain	• Snow melt • Train action
Consolidation - Compression	• Intense rain • Significant antecedent rain • Elevated phreatic surface	• Snow melt • Thaw • Train action
Consolidation - Earth Spread	• Intense rain • Significant antecedent rain • Elevated phreatic surface	• Snow melt • Thaw • Train action
Consolidation – Compression (peat)	• Intense rain • Significant antecedent rain • Elevated phreatic surface	• Snow melt • Thaw • Freeze thaw • Train action
Compression	• Intense rain • Significant antecedent rain • Elevated phreatic surface	• Snow melt • Thaw • Train action
Subgrade Dynamic Liquifaction	• Significant antecedent rain • Thaw	• Train action
Subgrade Dynamic Liquifaction - Earth Slide	• Train action	
Overall Settlement Hazard Scenarios	• Intense rain • Significant antecedent rain • Elevated phreatic surface	• Snow melt • Thaw • Train action

9.6.5 Suggested Settlement Hazard Events Trigger Causal Factors

Table 9-9 provides the author's suggested glossary and description of the trigger causal factors for settlement hazard events.

Table 9-9 Preliminary railway settlement hazard trigger causal factors.

Trigger Causal Factors - Settlement		Description
1.Geomorphological Processes		
		None identified
2.Physical Processes		
RSM	Rapid snow melt	Provides rapid recharge of water into the ballast trough reducing effective stress and shear strength in fouled ballast, subballast or subgrade can result in track failure.
SAR	Significant antecedent rainfall	Causes an abundance of free water saturating the ballast trough reducing effective stress and shear strength in fouled ballast, subballast or subgrade. Prolonged soaking will soften clay subgrades or saturate previously unsaturated silty subgrades weakening the subgrade for track failure under train loading.
IR	Intense rainfall	Provides rapid recharge of water into the ballast trough reducing effective stress and shear strength in fouled ballast, subballast or subgrade can result in track failure..
EPS	Elevated Phreatic Surface	Causes a build up of water pressures and a rise in the phreatic surface below the tracks. Prolonged artesian recharge will soften clay subgrades or saturate previously unsaturated silty subgrades weakening the subgrade for track failure under train loading.
T	Thawing	Downward thawing of the subgrade results in perched aquifers directly below the track, which can soften clay subgrades or saturate previously unsaturated silty subgrades weakening the subgrade for incremental failure under train loading. Process is particularly hazardous when ice lenses thaw after a frost heave.
Cn	Consolidation	Rapid consolidation of peat can trigger track failure by deflection of the track.

Trigger Causal Factors - Settlement		Description
Cm	Compression	Relatively rapid compression beneath the tracks can trigger track failure by deflection of the track.
SPD	Sub-grade plastic deformation	Incremental plastic deformation and settlement of the track resulting from local over-stressing and incremental plastic deformations of clay sub-grades from repetitive train loads can trigger track failure by deflection of the track.
SDL	Subgrade dynamic liquefaction	Incremental differential settlement localized to the track ballast and sub-grade, occurs in saturated fine-grained non-cohesive soils or fouled ballast and is the result of dynamic liquefaction induced by cyclic train loading can trigger track failure by deflection of the track.
4.Man-made or Animal Processes		
LSC	Shoulder over loading	Placement of waste debris on track roadbed shoulder or dumped over bank increases loading on the debris slope and oversteepens the slope increasing the destabilizing forces and potentially blocks seepage bringing the slope closer to failure.
TA	Train Action	Repetitive train loads causes Incremental subgrade plastic deformation and dynamic liquefaction of the subgrade resulting in track settlement
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can cause a rise in the phreatic surface under the tracks resulting in soften clay subgrades or saturation of previously unsaturated silty subgrades weakening the subgrade for incremental failure under train loading.

9.6.6 Suggested Collapse Hazard Events Trigger Causal Factors

Table 9-9 provides the author's suggested glossary and description of the trigger causal factors for collapse hazard events.

Piping/Dissolution Void Collapse

The prevalent trigger causal factors identified for piping/dissolution void collapse hazard scenarios include intense rain, significant antecedent rain, an elevated phreatic surface, freeze and most importantly train action.

Table 9-10 Suggested railway collapse hazard trigger causal factors.

Trigger Causal Factors - collapse		Description
2.Geomorphological Processes		
P	Piping	Subsequent piping of an existing piping void can trigger the collapse of the piping void resulting in track failure.
D	Dissolution	Subsequent dissolution of an existing dissolution void can trigger the collapse of the dissolution void resulting in track failure.
TD	Timber deterioration	Subsequent timber deterioration of previously deteriorated timber or timber that was holding open a void can trigger the collapse of the timber or the void it was holding open resulting in track failure.
3.Physical Processes		
IR	Intense rain	Intense rain can provide a rapid influx of water to initiate the collapse triggering processes of seepage or piping erosion or high water flows through culverts.
SAR	Significant antecedent rain	SAR can provide a sufficient influx of water to initiate the collapse triggering processes of saturation, seepage or piping erosion or high sustained water flows through culverts.
EPS	Elevated phreatic surface	Causes a build up of water pressures and a rise in the phreatic surface saturating liquefiable soils below the tracks triggering a liquefaction failure of the track grade.
CSS	Collapsing soils	Collapsing soils in the track sub-grade collapse, experience large and sudden reduction in volume, upon wetting triggering track failure.
Co	Corrosion	Corrosion causes the void formed by the culvert or around the culvert when soil trickles in from an opening caused by the corrosion to collapse triggering track failure.

Trigger Causal Factors - collapse		Description
CF	Culvert flow	Subsequent flow in a culvert erodes additional material from the previously formed voids outside of the culvert when soil is sucked in from the bottom by negative pressure from flowing water or is removed through erosion by water flowing outside of the culvert triggering track failure.
4.Man-made or Animal Processes		
TA	Train Action	Dynamic trainloads trigger a collapse track failure by over stressing a pre-existing void or by dynamic liquefaction of liquefiable soils beneath the track.
BA	Burrowing Animals	Subsequent burrowing triggers collapse hazard to occur resulting in track failure.
U	Utilities	Subsequent leaking utilities triggers collapse hazard to occur resulting in track failure.
M	Mining	Subsequent mining operations trigger collapse hazard to occur resulting in track failure.

9.7 Attributes for Subsidence Scenarios

Table 8-9 lists the subsidence hazard events with the author's suggested description of landform attributes for each. Note that any combination of these factors is an even stronger indicator that the given subsidence hazard exists.

Table 9-11 List of landforms associated with subsidence hazards

Subsidence Hazard	**Attribute Description**
Subgrade Plastic Deformation Hazards	• Appearance of mud ridges parallel to tracks one to three metres out from end-of-tie, on one or both sides. • Accelerated track surfacing maintenance required. • Frost heaving in areas where they typically have not formed in past. Sign of the development of ballast troughs and the production of non-cohesive fines from ballast abrasion ((ballast fouling)

Subsidence Hazard	Attribute Description
Consolidation Hazards	• Section of track passes through a peat bog or muskeg area. • Lateral wide berms have apparently sunk to surrounding ground level. • Thick ballast section balanced on either side. • Ground oscillates as train passes • Significant wear on track components, skewed ties and rounded tie bottoms
Compression Hazards	• High ballast that slopes off at greater than 2H:1V. • Ballast slopes off at end of tie due to low shoulder.
Subgrade Dynamic Liquifaction Hazards	• Mud spots start to occur. Common at bridge abutments, road crossings, switches and diamonds • SDL's are typically consistent with frost heave locations as they indicate presence of a ballast trough, non-cohesive fines either in the ballast or in the subgrade. • Evidence of a high phreatic surface such as ponding water, blocked ditches, seepage or piping erosion on slope.
Collapse Hazards	• Conical depressions in vicinity of track. • Open holes in ballast • Animal borrows in vicinity of tracks. • Evidence of piping or seepage erosion in vicinity of tracks. • Near by active or abandoned underground mining • Evidence of blocked or damaged culverts

9.8 Subsidence Hazard Scenarios Consequence Likelihood Factors

9.8.1 Track Vulnerability

Table 9-12 summarizes the author's list of suggested track vulnerability factors corresponding to the mode of track failure and the type of subsidence hazard.

Table 9-12 Listing of the track failure attributes corresponding to the modes of track failure and earth landslide hazard events.

Modes of Track Failure *.... ground hazards may cause a track failure by:*	**Causative Ground Hazards**	**Track Vulnerability Factors**
Removing support from the track structure	• Settlement • Collapse	• Size, gradation and compaction of subgrade material. • Shoulder width • Ballast, sub ballast quality • Track drainage

Modes of Track Failure *…. ground hazards may cause a track failure by:*	**Causative Ground Hazards**	**Track Vulnerability Factors**
Deflecting the track rail surface,	- Settlement - Collapse	- Track geometry (curves and spirals are more susceptible) - Train loading - Track surface - Shoulder width - Ballast, sub ballast quality
Damaging the track components	- Settlement (Compression)	- Continuous welded track - Concrete ties

9.8.2 Service Disruption Vulnerability

The service disruption vulnerability factors for subsidence scenarios given that track failure has occurred include site access, available material and equipment, presence or absence of warning devices such as cross level detectors, train speed, sight lines, grades, and traffic frequency. More details on these factors are given in Section 4.6.2.

9.8.3 Derailment Vulnerability

The derailment vulnerability factors for subsidence scenarios given that track failure has occurred include presence or absence of warning devices such as tip over posts or cross level detectors, train speed, sight lines, grades and traffic frequency. More details on these factors are given in Section 4.6.3.

9.9 Summary

From Chapter 3 accidents from settlement hazard events, occurred at a frequency of 1.4 per year, severity of $28,000 direct costs per accident accounting for $40,000 per annum occurring mainly in the interior plains presumably due to weak clay subgrades and lack of drainage. The chapter characterizes the identified subsidence hazard scenarios from the CN Western Canada ground hazard database that contributed to these loss records.

39% of the hazard locations were *subgrade plastic deformation*, 33% were *consolidation*, 25% were *compression and* 3% were *sub-grade dynamic liquefaction* scenarios. Sub-grade dynamic liquefaction hazards are under represented.

No hazard scenarios initiating with collapse events were identified however a collapse hazard event is included in an overland / through flow erosion scenario.

SPD and SPD – E(Em)SI scenarios involve incremental plastic deformation and settlement from local over-stressing and incremental plastic deformations of clay sub-grades from repetitive train loads. In the latter scenario, a rupture surface can form through the cohesive embankment fill. Track failure from all these scenarios occurs by removal of track support or track deflection.

Cn – Cm, Cn – E(peat)Sp and Cn – Cm(peat) hazard scenarios occur in embankments on peat or consolidating clays. Cn – Cm scenarios result from a high ballast section, Cn – E(peat)Sp scenarios involves consolidation of the peat followed by a stiffer embankment fill failing into a much weaker peat foundation with corduroy timber mat failures suspected. Cn – Cm(peat) scenarios involve jostling around of the track during train action due to low stiff elastic compression of the fully consolidated peat substrata. In all scenarios track failure occurs by removal of track support or track deflection.

Simple Cm scenarios involve differential compression and settlement associated with poorly compacted, dumped fills, track lined off the embankment or lifted too high such that lateral confinement is removed and compression settlement occurs in the ballast. Track failure occurs by removal of track support or track deflection.

SDL and SDL – ESI scenarios initiate with dynamic liquefaction induced by cyclic train resulting in incremental differential settlement in the ballast and sub-grade due to saturated fine-grained non-cohesive soils or fouled ballast. Ballast troughs are associated with SDL hazard events. SDL – ESI scenarios occur on embankments where water flows along ballast trough out of cut sections into the ballast pocket on a predominantly silt embankment. Saturation of the upper silty portion of the embankment creates a potential earth slide event. Track failure occurs by removal of track support or track deflection.

Consolidation occurs in saturated soils of low permeability such as peat and clays. Bank widening, slope flattening and berming, change the loading condition and may re-activate the consolidation process.

Compression involves a volume decrease caused by a system of forces. Most railway compression hazards involve differential compression and settlement of poorly compacted fills; thick, unconfined ballast; or heterogeneous fills and occur under train loading or overburden pressures. Fully consolidated peat sub-grades behaves as a low stiffness elastic material which deflects after each wheel loading setting up ground surface waves in front of each wheel set resulting in accelerated wear of track components.

S*ubgrade plastic deformation* involves incremental local over-stressing and shearing of weak clay sub-grades similar to bearing capacity failure. Deformations accelerates as ballast trough forms trapping water causing clay softening and are sustained through cyclic track lifting and settlement. A case example illustrates the latter stages of a subgrade plastic deformation event.

Subgrade dynamic liquefaction (SDL) hazard events result from excess pore pressures and reduction of shear strength in the saturated fouled ballast or silty subgrade during cyclic train loading. Over time, incremental minor shear strains causes production of additional fines from abrasion of the ballast which accelerates the process eventually leading to track failure by track deflection. SDL commonly occurs during frost heave thawing due to the common preparatory causal factors of saturated silty soils immediately below the tracks.

Collapse hazard events typically involve collapse into preexisting voids formed by piping, dissolution, damaged or deteriorating culverts, buried timber, burrowing animals, large uniform loose rock fill or mining. A case example illustrates how the propensity for the piping voids to stay open in the calcareous silt contributed to a collapse caused track failure and derailment. Liquefaction collapse hazards involve collapse into underlying liquefied soils triggered by cyclic earthquake loading. Settlement Hazard Scenarios Rates of Ground Hazard System Failure

Observations indicate that rates of track failure are predominantly slow for the four settlement initiated scenarios. Rapid track failure was suggested if the track was suspected to fail under train loading.

The timing of most of the settlement scenarios is incremental with train loading with the notable exception of Cn - E(Pt)Sp scenarios which are suggested to occur triggered by significant antecedent rain or exposure of the corduroy base to aerobic conditions. The lag time between hazard events for these scenarios range from weeks to decades.

Once identified settlement hazard scenarios remain in the *Stable – monitoring required* track stability state and move to *Marginally Stable* if the track surface can not be maintained between trains.

Once identified collapse hazards involving voids beneath the track would fall into marginal stable state. Track stability of liquefaction collapse hazards requires assessment of vulnerability of the hazard scenario to the trigger causal factor.

Observed preparatory causal factors for Subgrade Plastic Deformation Scenarios include a low shear strength cohesive subgrade, increased train loading, poor drainage, presence of a ballast trough and reduction of the structural fill section.

Observed preparatory causal factors for Consolidation hazard scenarios include ponding or high water tables, plugged or non-existent ditches, presence of a peat, poorly drained conditions, frequent bedrock knobs in peat areas and rotting corduroy.

Observed preparatory causal factors for compression hazards include thick ballast sections and track being lined to the edge of the embankment top surface both of which reduce lateral support for the ballast.

Observed preparatory causal factors for Subgrade Dynamic Liquefaction scenarios include silty subgrades, ballast at the end of its design life, ballast pockets, high impact locations, ponding water, an elevated phreatic surface, poor drainage and thawing of ice lenses at frost heave locations. Suggested preparatory causal factors for settlement hazards include:

Ground Conditions:

- Poorly compacted or dumped fills
- Weak clay sub-grades
- Fine-grained non-cohesive soils or fouled ballast
- Liquefiable soils

Physical Processes

- Low level Intense snow melt
- Significant antecedent rainfall
- Intense rainfall
- High groundwater recharge

Geomorphological Processes

- Frost heaves

Man-made or animal processes

- Train Action
- Blocked drainage

- Thawing
- Consolidation
- Compression
- Sub-grade plastic deformation
- Sub-grade dynamic liquifaction

Suggested preparatory causal factors for collapse hazards include:

Ground Conditions:

- Peat sub-grade
- Voids in rock fill
- Timber in sub-grade
- Piping susceptible soil
- Dissolution susceptible rock
- Collapsing soils
- Liquefiable soils

Physical Processes

- High groundwater recharge
- Culvert failure

Geomorphological Processes

- Piping
- Dissolution
- Timber deterioration

Man-made or animal processes

- Train Action
- Blocked drainage
- Burrowing Animals
- Utilities
- Mining

The prevalent observed trigger causal factors for *subgrade plastic deformation* scenarios are intense rain, an elevated phreatic surface immediately under the tracks, snow melt, and train action; for *consolidation scenarios* are intense rain, an elevated phreatic surface in the peat, snow melt or frost thawing at the surface of the peat; for *compression* scenarios are intense rain, an elevated phreatic surface in the peat, snow melt or frost thawing at the surface of the peat; and for *subgrade dynamic liquefaction* hazard scenarios are significant antecedent rain, snow melt, frost thaw from a frost heave.Suggested trigger causal factors for settlement include:

Geomorphological Processes

- None suggested

Man-made or animal processes

- Shoulder over loading
- Train Action
- Blocked drainage

Physical Processes

- Rapid snow melt
- Significant antecedent rainfall
- Intense rainfall
- Elevated Phreatic Surface
- Thawing
- Consolidation
- Compression
- Sub-grade plastic deformation
- Subgrade dynamic liquefaction

The prevalent observed trigger causal factors for piping/dissolution void collapse hazard scenarios include intense rain, significant antecedent rain, an elevated phreatic surface and train action.

Suggested trigger causal factors for collapse hazards include:

Geomorphological Processes

- Piping
- Dissolution
- Timber deterioration

Man-made or animal processes

- Train Action
- Burrowing Animals
- Utilities
- Mining

Physical Processes

- Intense rain
- Significant antecedent rain
- Elevated phreatic surface
- Collapsing soils
- Corrosion
- Culvert flow

For subgrade plastic deformation hazards revealing factors include mud ridges, accelerated track surfacing, and frost heaving. For consolidation hazards revealing factors include peat bogs, sunken berms, thick ballast sections, oscillating ground as train passes and significant wear on track components. For compression hazards the revealing factors is high ballast. For subgrade dynamic liquefaction hazards revealing factors include mud spots, frost heave locations and evidence of a high phreatic surface. For collapse hazards revealing factors include conical depressions, open holes in ballast, animal borrows and evidence of piping or seepage erosion, mining and blocked or damaged culverts.

Track vulnerability factors for subsidence hazard scenarios include size, gradation and compaction of subgrade material, shoulder width, ballast and sub ballast quality, track drainage, track geometry, train loading, track surface, continuous welded vs. jointed rail and concrete vs. timber ties.

The service disruption and derailment vulnerability factors for subsidence scenarios include site access, material and equipment availability, warning devices, train speed, sight lines, grades, and traffic frequency.

Chapter 10 Characterization of Railway Overland / Through Flow Erosion Hazard Scenarios: CN Western Canada

10.1 Introduction

Hydraulic erosion involves removal of soil particles or rock by the action of flowing waters. As presented in Section 2.4, Level III categorization of railway hydraulic erosion hazards, based on the slope hydrologic cycle, is into overland flow, through flow and sub-aqueous flow. This chapter combines characterization of both overland and through flow erosion, hazard scenarios and hazard events. Table 10-1 presents a summary from Chapter 3 of the direct losses from train accidents caused from overland / through flow erosion hazard events, often referred to as *washouts*, for CN across Canada in 1992-2002. It is evident from these statistics that overland / through flow hazard events represent a significant risk to CN railway operations in Canada.

Table 10-1 Summary of train accident losses caused from overland / through flow hazard events, CN Canada wide 1992-2002

Hydraulic Erosion Hazard Event	**Frequency (events/year)**	**Severity (direct costs/event)**	**Annual Cost (cost/year)**
Overland Flow Erosion	1.1	411,000	**452,000**
Through Flow Erosion	0.4	820,000	**328,000**
Combined	**1.5**	**520,000**	**780,000**

Overland flow erosion was was the most frequent in the Longlac to Winnipeg corridor where the majority of the events were associated with intense rain storms. These hazards are made more severe by significant beaver activity in these areas. The most significant through flow hazard event occurred on the Kinghorn Subdivision in the vicinity of Orient Bay in the Spring of 1994. The inferred cause of the grade failure in this case was a piping failure brought on by a groundwater recharge following a seasonal snow melt (TSB, 1996).

This chapter steps through the characterization of the identified overland / through flow erosion hazard scenarios from the CN Western Canada ground hazard database that would have contributed to these loss records. Following an illustration and description of the hazard scenarios initiating with overland / through flow erosion hazard events, the chapter characterizes overland / through flow erosion hazard ground conditions and processes, rates and timing of system failure and track stability states. This is followed by identification and characterization of overland / through flow erosion hazard events preparatory and trigger causal factors either observed or interpreted by the author followed with an identification of overland / through flow erosion revealing factors. The chapter closes with a summary of overland / through flow erosion hazard scenarios consequence likelihood factors for track failure, service disruption and derailment.

10.2 Overland / Through Flow Erosion Hazard Scenarios FMEA

The short list of six identified hazard scenarios initiating with overland / through flow erosion hazard events is presented in Table 8-2. The following sections describe each of the hazard scenarios.

Table 10-2 Summary of Overland / Through flow hazard scenarios CN Western Canada

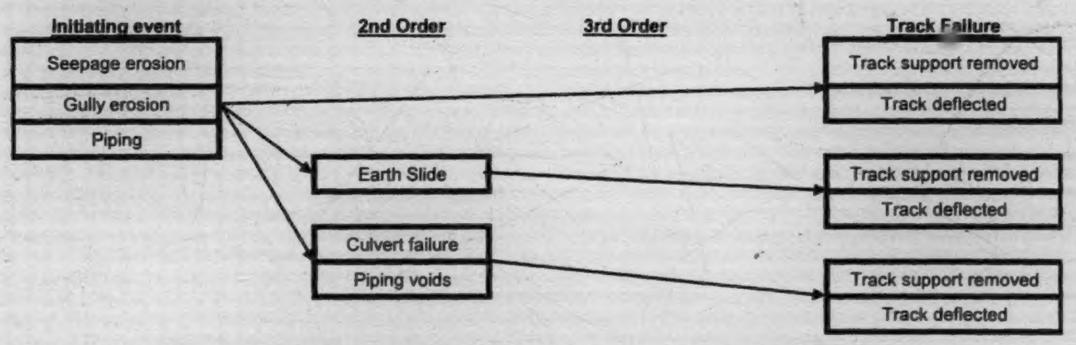
Level		Ground Hazard Scenario	Coding	#
I	II			
Hydraulic Erosion	Overland / Through Flow Erosion	**Overland / Through Flow Erosion**		
		Seepage Erosion / Piping / Gully Erosion-Earth Slide / Culvert Failure / Piping Void Collapse	SE / P / GE - ESI - / CF / PD -	50
		Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide	SE / SW / GE - ESI -	46
		Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow	SE / SW / GE - SE / GE / - ESI - EFw -	24
		Seepage Erosion - Earth Slide - Earth Flow	SE - ESI - EFw -	12
		Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow	SE / GE - ESI - EFw -	12
		Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall	SE / SW / GE - DF -	7
		Subtotal		151

10.2.1 Seepage Erosion / Piping / Gully Erosion- Earth Slide / Culvert Failure / Piping Void Collapse

Figure 10-1 depicts a simplified FMEA for Seepage Erosion / Piping / Gully Erosion-Earth Slide / Culvert Failure / Piping Void Collapse hazard scenarios. The records indicate that most if not all of these hazard scenarios involve a culvert which appears to be blocked, damaged, poorly arranged or under sized or there is some indication that some of these processes have been active in the past. The initial hazard event involves water running either on the outside of a culvert due to a surcharged inlet or out of the culvert through a damaged location. These flows have a potential to cause seepage erosion, piping or gully erosion due to overtopping of the rail grade. These processes can lead directly to track failure or cause 2nd order events such as an earth slide or collapse failures such as culvert failure or collapse of pre-existing piping voids. All of these hazard events can cause track failure by either support being removed from tracks or by deflecting the track.

Overland / Through Flow Erosion **Total count: 151**

Seepage Erosion / Piping / Gully Erosion- Earth Slide / Culvert Failure / Piping Void Collapse	**SE / P / GE - ESI / CF / PD -**	**Count: 50**

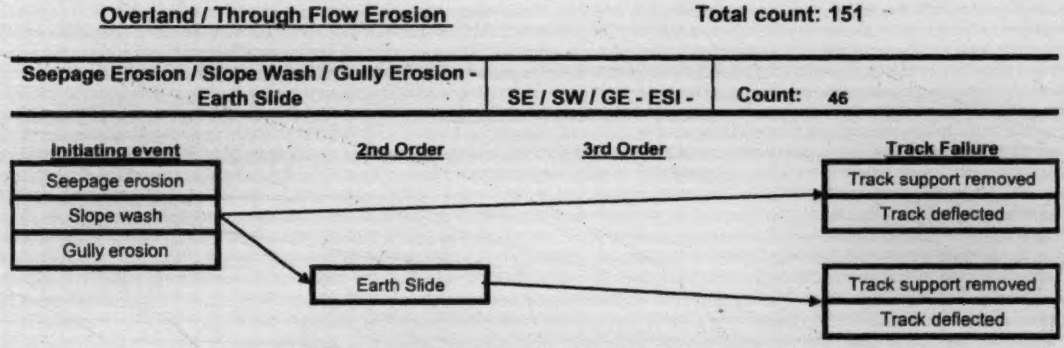

Initiating event
2nd Order
3rd Order
Track Failure
Seepage erosion
Gully erosion
Piping
Earth Slide
Culvert failure
Piping voids
Track support removed
Track deflected
Track support removed
Track deflected
Track support removed
Track deflected

Notes:
1. Most involve culvert with blockage, damage, poor arrangement or undersized
2. Damage from high water flows can lead to ESI or Collapse from CF or PD voids.

Figure 10-1 Simplified FMEA for Seepage Erosion / Piping / Gully Erosion- Earth Slide / Culvert Failure / Piping Void Collapse hazard scenarios.

10.2.2 Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide

Figure 10-2 depicts a simplified FMEA for Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide hazard scenarios. Most of these scenarios involve seepage, slope wash or gully erosion of the lower slope which serves to undermine the shoulder of the track increasing the likelihood of track failure directly or can change the slope geometry such that an earth slide may occur. When the first order erosion involves removal of the track shoulder the earth slide may be caused by train loading. These scenarios can cause track failure by either removing support from the track or by deflecting the track.


Overland / Through Flow Erosion
Total count: 151
Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide
SE / SW / GE - ESI -
Count: 46
Initiating event
2nd Order
3rd Order
Track Failure
Seepage erosion
Slope wash
Gully erosion
Earth Slide
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. Most involve lower slope where ongoing SE, SW or GE serve to undermine track shoulder
2. With shoulder support gone potential for earth slide from train loading exists.

Figure 10-2 Simplified FMEA for Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide hazard scenarios

Figure 10-3 illustrates a case example of a Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide hazard scenario that occurred following significant runoff following an intense rain event. Erosion may be from both overland flow and through flow.

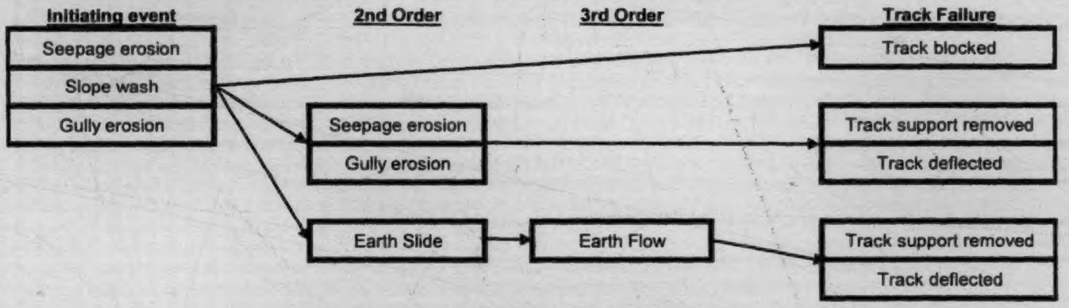
Figure 10-3 Case example of a Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide hazard scenario at Mile 94.2 of CN's Ashcroft Subdivision (photo by Tim Keegan taken November 16,2006, CN File 4670-ASH-94.2)

10.2.3 Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow

Figure 10-4 depicts a simplified FMEA for Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow hazard scenario. This complex hazard scenario involves material eroded by seepage, slope wash or gully erosion of an earth slope above the tracks depositing in the ditch or culvert creating a blockage of flow. The ponded water can either flow over or through the track grade creating the second order seepage erosion, gully erosion or earth slide – earth flow parallel hazards. The first order hazard events could deposit enough material on the tracks to fail the track by blockage. The second and third order hazard events can cause track failure by either removing support from the track or by deflecting the track.

Overland / Through Flow Erosion Total count: 151

Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow	**SE / SW / GE - SE / GE / - ESl - EFw -**	**Count:** 24


Initiating event
2nd Order
3rd Order
Track Failure
Seepage erosion
Slope wash
Gully erosion
Seepage erosion
Gully erosion
Earth Slide
Earth Flow
Track blocked
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. Initiating event from upper slope from high phreatic surface and seepage line. Excessive sediment either buries track or blocks drainage, ditchs and culverts.
2. Blocked drainage forces water flow over or through track grade.
3. Saturated earth slide material looses cohesion and converts to earth flow.

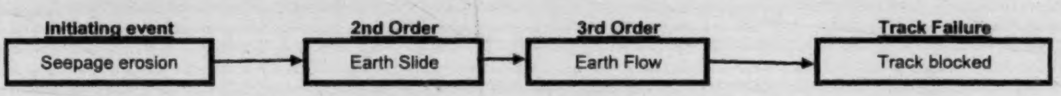
Figure 10-4 Simplified FMEA for Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow hazard scenario.

10.2.4 Seepage Erosion - Earth Slide - Earth Flow

Figure 10-5 depicts a simplified FMEA for the Seepage Erosion - Earth Slide - Earth Flow hazard scenarios. The distinction between this scenario and Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide hazard scenarios is that these scenarios typically initiate with seepage erosion at the toe of the slope above the tracks due to an elevated phreatic and seepage surface. The combination of an undermined toe and elevated phreatic surface that can result in an earth slide hazard event which, due to saturation of the non-cohesive earth, typically converts to an earth flow. The earth flow material ends up on the track causing track failure by blockage. Often these scenarios are associated with relatively shallow sloping bedrock which serves to concentrate and direct the seepage flows down slope. Figure 10-6 provides two case examples of this hazard scenario on the Albreda at different activity stages within the scenario.

Overland / Through Flow Erosion **Total count: 151**

Seepage Erosion - Earth Slide - Earth Flow	**SE - ESl - EFw -**	**Count:** **12**


Initiating event
Seepage erosion
2nd Order
Earth Slide
3rd Order
Earth Flow
Track Failure
Track blocked

Notes:
1. SE from high phreatic surface and concentrated seepage undermines upper slope
2. Combined high phreatic surface and undermined slope results in earth slide
3. Saturated non-cohesive earth slide material looses cohesion and converts to earth flow.

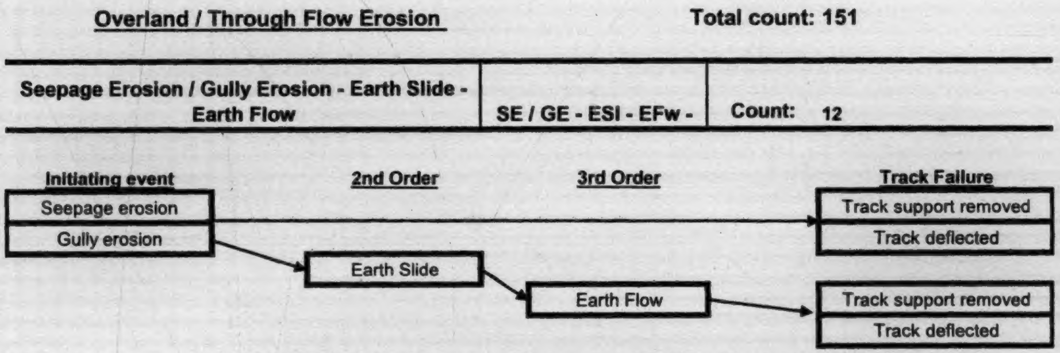
Figure 10-5 Simplified FMEA for Seepage Erosion - Earth Slide - Earth Flow hazard scenarios.

Seepage Erosion
5/1/2001
5/7/1999 1:18pm

Figure 10-6 Case examples of a Seepage Erosion - Earth Slide - Earth Flow hazard scenarios at Mile 107(above) and Mile 116.8(below) of CN's Albreda Subdivision (photos by Tim Keegan, CN Files 4670-ABD-107 and 4670-ABD-107)

10.2.5 Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow hazard scenarios.

Figure 10-7 depicts a simplified FMEA for Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow hazard scenarios. These scenarios typically are identified by evidence of seepage or gully erosion on the slope below or downstream of the track. Those that have failed have either had the seepage and gully erosion retrogress up and under the track removing track support or deflecting the track or have caused earth slides to occur when, because there are high phreatic surfaces in non-cohesive earth, the slides convert to a flow. In other events the earth slide – earth flow events occurred after a rapid draw-down of the water level has occurred following a rapid gully erosion of an embankment or a culvert surcharge is suddenly released. Figure 10-8 illustrates a case example of this scenario where the embankment initially failed by gully erosion as water over topped it. The subsequent rapid draw-down of water caused a significant length of the remaining embankment to fail as an earth slide – earth flow event. This scenario causes track failure by either deflecting the track surface or by removing support from the track structure.


Overland / Through Flow Erosion
Total count: 151
Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow
SE / GE - ESl - EFw -
Count: 12
Initiating event
2nd Order
3rd Order
Track Failure
Seepage erosion
Gully erosion
Earth Slide
Earth Flow
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. High phreatic surface and seepage line results in SE, GE or P undermining toe of lower slope.
2. Combined train loading, high phreatic surface and undermined slope results in earth slide
3. Saturated non-cohesive earth slide material looses cohesion and converts to earth flow.

Figure 10-7 Simplified FMEA for the Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow hazard scenarios.

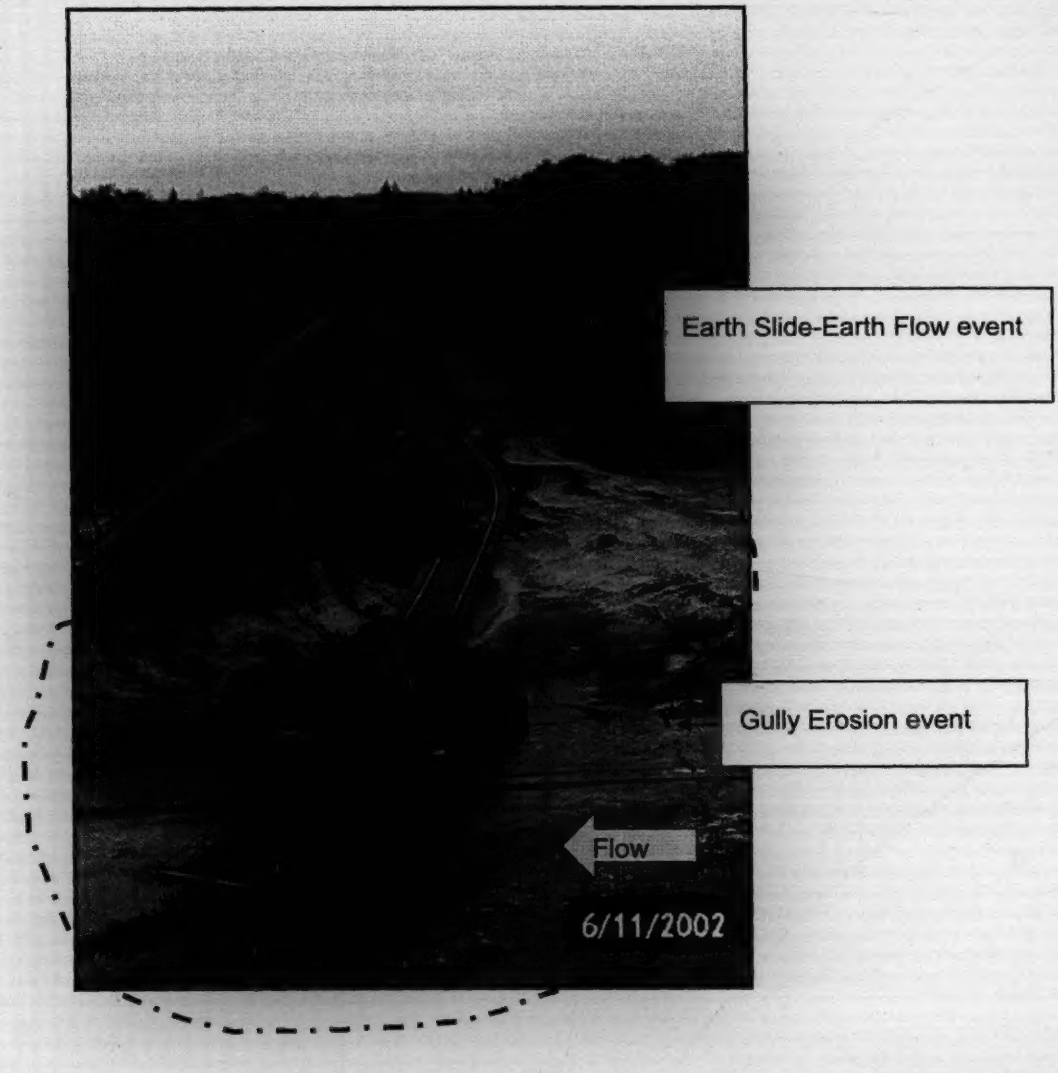


Figure 10-8 Case example of a Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow hazard scenario at Mile 23.2 of CN's Ft Francis Subdivision (photo by Tim Keegan, CN File 4670-FTF-23.2)

10.2.6 Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall

Figure 10-9 depicts a simplified FMEA for Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall hazard scenario. These scenarios are typically identified on slopes above the tracks that contain a range of soil particle sizes from fine to boulders. Processes of seepage, slope wash and gully erosion are evident and act to remove fines from around larger particles resulting in debris fall events which can cause track failure by either blocking the track or damaging track components.

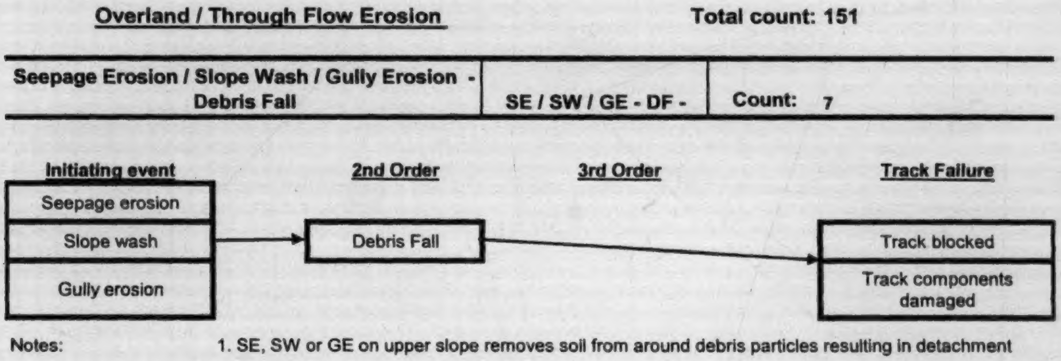

Overland / Through Flow Erosion
Total count: 151
Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall
SE / SW / GE - DF -
Count: 7
Initiating event
2nd Order
3rd Order
Track Failure
Seepage erosion
Slope wash
Gully erosion
Debris Fall
Track blocked
Track components damaged
Notes:
1. SE, SW or GE on upper slope removes soil from around debris particles resulting in detachment

Figure 10-9 Simplified FMEA for Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall hazard scenario

10.3 Overland / Through Flow Erosion Hazard Events Ground Conditions and Processes.

Hydraulic erosion involves removal of soil particles or rock by the action of flowing waters. Level III classification of railway hydraulic erosion hazard events is based on the slope hydrologic cycle into overland flow, through flow and sub-aqueous flow erosion. This section describes the ground conditions and processes characteristic of both overland and through flow erosion hazard events. The Level IV categorization of these hazards is based on process type as described in the railway hydraulic erosion hazard classification system presented in Chapter 2. The following sections describe the ground conditions and processes for these process based ground hazards.

10.3.1 Overland Flow: Slope Wash

Slope wash occurs when rainfall or snow melt impacts and loosens soil particles, which then move with the water. It can occur in sheets or rills, and can initiate gullies. Slope wash is generally associated with rainfall and depends on the magnitude, duration, intensity and frequency of rainfall, the infiltration characteristics of the soil, the length and angle of the slope and the soil surface characteristics. The impact of raindrops loosens soil particles that then start to move with the water. On uniform slopes, water concentrates into rills, resulting in shallow gullies down the face of the slope. After Ritter (2002) the amount of erosion that occurs is a function of:

- *Rainfall* - Volume, duration, intensity and frequency are all factors affecting erosion. The greatest amounts of erosion are associated with high intensity, short duration, and frequent rainfalls.
- *Soil characteristics* - particle size, settling velocity, relative density, shape, state of dispersion and cohesion are all factors affecting erosion. Erosion is greatest with fine-grained cohesionless soils, for example, fine sands and silts. Coarse materials, such as gravels, resist erosion due to large particle size. Clays are also resistant as cohesion prevents soil particles from being loosened.
- *Slope angle* - a fourfold increase on the slope vertical drop gives a 2X increase in water velocity; 4X increase in water cutting capacity; 32X increase in quantity of material carried by water; and 64X increase in the size of particle that can be transported.
- *Vegetation* prevents erosion by interception and evaporation of raindrops; providing a protective shield against impact of raindrops; soil suction through the effect of roots; increasing infiltration through the cavities of decaying roots; and reducing velocity through increased friction.

Slope wash can typically lead to debris falls as finer more easily eroded particles are first removed from around coarser debris particles eventually causing them to dislodge. Processes of wind and train vibrations have also been observed to trigger the debris falls.

10.3.2 Overland Flow: Gully Erosion

A gully erosion hazard event involves initiation of a channel on a sloping surface caused when the erosive forces of concentrated overland flows surpasses the resistance of the surface being eroded. Once water is focused into channels, this positive feedback process promotes continued evolution of channel networks at the expense of unconfined sheet flow (Ritter, 2002).

More severe gully erosion events are the result of either channel avulsion or overtopping of embankments whereby flows are redirected down a steep slope of erodible material.

Gully erosion by overtopping commonly results in catastrophic failure of the rail grade as it involves the sudden release of impounded water comparable to a dam burst scenario. Overtopping failure of an embankment initiates with rapid gully erosion on the downstream slope and rapidly erodes back through the embankment. Once the gully reaches the upstream side of the embankment and the effective crest or spillway of the embankment starts to lower, any impounded water behind the embankment starts to release exponentially increasing the flows and erosion forces in the gully. Often these types of rail grade failures occur in combination with seepage erosion or an earth slide or flow on the downstream slope brought on by the high pore pressures built up in the slope.

Since haul roads, ditches and pre-existing gullies concentrate drainage, they are particularly prone to gully erosion. Gully erosion is generally dependent on the factors identified for slope wash events. Excessive erosion in ditches increases the effective slope height and slope angle of cuts and embankments, increasing the potential for earth slide events.

10.3.3 Through Flow: Seepage Erosion

Seepage erosion occurs when the exit velocity of groundwater is sufficient to cause particle erosion. As erosion moves into the slope, the hydraulic gradient is increased due to a shortened flow path which further increases exit velocities and seepage erosion. Erosion proceeds rapidly up gradient undermining the slope and can completely erode the track grade.

Seepage erosion is typically associated with saturated slopes of erodible materials typically SM or ML. Using Cruden and Varnes (1996) terminology the seepage front typically retrogresses on the slope which is most difficult if it retrogresses into the track subgrade.

Solifluction is a common type of seepage erosion which involves the thawing of near surface frost in a fine grained non-cohesive slope. As the thaw line moves into the slope the saturated non-cohesive soil can't drain and essentially flows down slope. The accumulating flow material can result in blocked drainage acting as a preparatory cause for other ground hazards.

10.3.4 Through Flow: Piping

Piping occurs when water flowing through material opens a tunnel or pipe that remains open and continues to erode material. Piping is dependent on the soil's permeability, preferential flow paths, ability to maintain an arched opening, chemical makeup and the erosive nature of the material. As piping progresses the flow path shortens, the hydraulic gradient is increases and the piping accelerates up the flow path. Typically it is associated with easily eroded soils such as silts and fine silty sands. It can develop around culverts if the backfill is loose and voids exist. Burrowing rodents, such as moles, gophers and badgers, have been known to cause piping failures when the burrows shorten the groundwater flow path and exit velocities become sufficient to begin the piping erosion process.

10.3.5 Through flow: Culvert Erosion

Erosion processes associated with culverts include water running out or into an opening in the culvert, soil being sucked in through an opening in the culvert by negative pressure from flowing water in the culvert, and water running along the preferential flow path outside of the culvert driven by a surcharge at the inlet of the culvert due to a backup into the culvert caused by debris or ice blockage at either the inlet or outlet, an under capacity culvert or a buoyancy failure of a surcharged inlet.

Culvert erosion can occur at the inlet, the outlet, or around a culvert or can be the result of a partial or complete blockage. Causal factors may include insufficient culvert capacity during high flow periods or blockage due to ice buildup. Inability for the culvert to pass the flow volumes for any reason can results in a surcharge of the culvert, excessive seepage erosion of the down stream slope, gullying if overtopped or rapid draw down conditions .

10.3.6 Through flow: Dissolution

A dissolution hazard event involves erosion of voids in rock developed by solution which may progress to where the voids undermine the track grade or undermine a slope creating a rock fall, rock slide or dissolution collapse hazard. Typically it occurs in soluble rocks such as limestone, dolomite or gypsum and is associated with karst topography.

10.4 Overland / Through Flow Erosion Hazard Scenarios Rates of Ground Hazard System Failure

Figure 10-3 presents a summary of the rates of track failure estimted by the author for the CN Western Canada overland and through flow erosion hazard scenarios. The rates reported for all six scenarios range from slow to rapid reflecting the rates of track failure associated with the various ultimate hazard events in each scenario which range from incremental seepage erosion to earth slide - earth flows and collapse hazard events.

Table 10-3 Rates of tracks failure recorded for overland / through flow erosion hazard scenarios

				Percentage of Ground Hazards Reporting this Speed				
Level III Subgroups	**Ground Hazard Scenario**	**Coding**	**Count**	**Very Rapid**	**Rapid**	**Moderate**	**Slow**	**Very Slow**
Overland / Through Flow Erosion	**Overland / Through Flow Erosion**							
	Seepage Erosion / Piping / Gully Erosin- Earth Slide / Culvert Failure / Piping Void Collapse	SE / P / GE - ESI - / CF / PD -	50	2%	12%	28%	22%	4%
	Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide	SE / SW / GE - ESI -	46	0%	15%	41%	4%	4%
	Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow	SE / SW / GE - SE / GE / - ESI - EFw -	24	0%	13%	17%	17%	0%
	Seepage Erosion - Earth Slide - Earth Flow	SE - ESI - EFw -	12	0%	8%	8%	17%	8%
	Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow	SE / GE - ESI - EFw -	12	0%	17%	25%	33%	0%
	Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall	SE / SW / GE - DF -	7	0%	14%	0%	29%	0%
		Subtotal	**151**	**1%**	**13%**	**27%**	**17%**	**3%**

As for timing within these scenarios, overland flow events occur relatively quickly after the climate event that provides the source of water flow such as rainfall or snow melt and the magnitude of the event depends on the return period of the specific climatic event. Through flow hazard events tend to be incremental and there is a built in time lag depending on the permeability, hydraulic gradient and length of flow path. Table 10-4 provides the author's subjective estimate of the timing of the hazard events and the lag time between the events that make up the various scenarios in this subgroup.

Table 10-4 Author's suggested timing and estimated time lag for overland / through flow erosion scenarios.

Overland/Through Flow Erosion Scenario	Timing of Individual event	Lag Time Between Events
SE / P / GE – Esl / CF / PD -	• SE / P : Following significant antecedent rain or snow melt • GE : Following intense rain or snow melt • ESI / CF / PD : During or shortly after intense rain or snow melt	• Days to years
SE / SW / GE - ESI -	• SE: Following significant antecedent rain or snow melt • SW / GE : During or shortly after intense rain or snow melt • ESI : Incremental with train loading	• Months to years
SE / SW / GE - SE / GE / - ESI - EFw -	• SE: Following significant antecedent rain or snow melt • SW / GE : Following intense rain or snow melt • ESI - EFw : During or shortly after intense rain or snow melt	• Days to years
SE - ESI - EFw -	• SE: Following significant antecedent rain or snow melt • ESI - EFw : During or shortly after intense rain or snow melt	• SE-ESI:Days to years • ESI-EFw:Seconds to minutes
SE / GE - ESI - EFw -	• SE: Following significant antecedent rain or snow melt • GE : During or shortly after intense rain or snow melt • ESI - EFw : During or shortly after intense rain or snow melt	• SE/GE -ESI: Days to years • ESI-EFw:Seconds to minutes
SE / SW / GE - DF -	• SE: Following significant antecedent rain or snow melt • SW / GE : During or shortly after intense rain or snow melt	• Minutes to days

10.5 Overland / Through Flow Erosion Hazard Scenarios Track Stability States.

Since by nature, hazards in these scenarios are typically not identified until preparatory process causal factors such as evidence of overland or through flow erosion are apparent, the majority of these sites tend to exist in the (3) *Stable - monitoring required* track stability state. If trigger causal factors such as intense or significant antecedent rain, snow melt or a rise in the phreatic surface become apparent these sites will move into the Marginally Stable Track Stability State provided the particular ground hazard event can directly result in track failure.

10.6 Overland / Through Flow Erosion Hazard Scenarios Preparatory Causal Factors

10.6.1 Observed Overland/Through Flow Erosion Hazard Scenario Preparatory Causal Factors

Error! Reference source not found. presents the preparatory causal factors identified for each overland/through flow erosion hazard scenario. A summary of the more prevalent preparatory causal factors recorded for each overland/through flow erosion scenario is listed in Table 10-1. The following sections discuss the results for each individual hazard scenario in the sub group.

10.6.1.1 Seepage Erosion / Piping / Gully Erosion- Earth Slide / Culvert Failure / Piping Void Collapse Hazard Scenario Preparatory Causal Factors

The prevalent preparatory causal factors recorded for the Seepage Erosion / Piping / Gully Erosion- Earth Slide / Culvert Failure / Piping Void Collapse scenarios tend to be indicators that the culvert is compromised by external or internal erosion, blockage or poor arrangement of the culvert. As well, they indicate there is a higher likelihood of problems with flow through the culvert due to the existence of beaver habitat. These scenarios are typically associated with pulled apart culverts and erosion around a culvert inlet or outlet. Figure 10-10 provides an example of a pulled apart culvert, and associated collapse feature above the pull apart. These features are indicators of potential internal erosion from water running out or soil falling in through the pull apart and ultimately resulting in activation or reactivation of an earth slide. These can also be an indication of an icing culvert; the pulled apart culvert may be the result of the culvert plugging with ice at the outlet which caused water to back up raising the pore pressures in the embankment and a partial earth slide in the downstream slope which pulled the culvert apart. Preparatory causal factors for this specific hazard scenario would include seepage entering the culvert through the joints and discharging from the outlet.

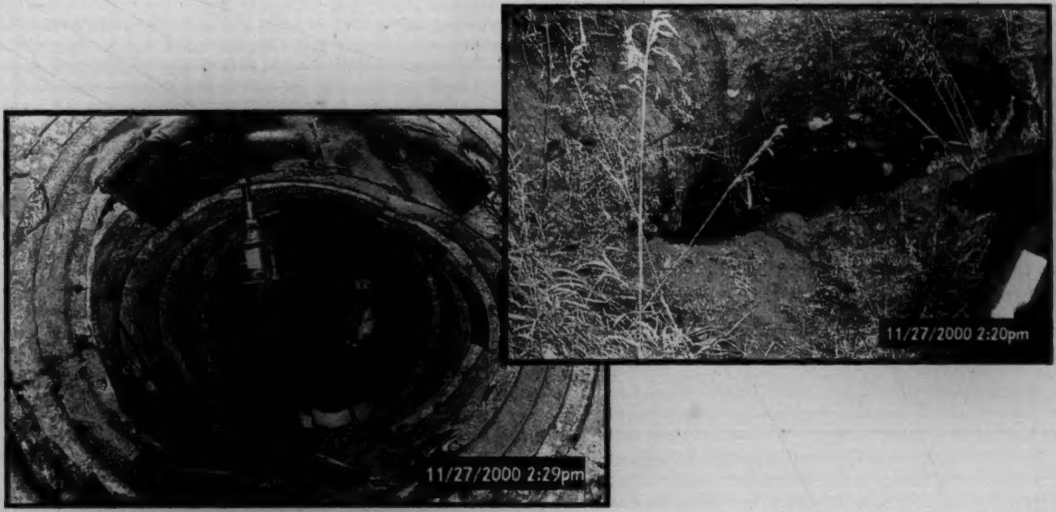


Figure 10-10 Photos of pulled apart culvert (left) and collapse feature (right) as an example of a preparatory cause for a Seepage Erosion / Piping - Earth Slide hazard scenario. (Mile 148.22 CN Wainwright Subdivision, photo by Tim Keegan, CN File 4670-WWR-148.22)

10.6.1.2 Seepage Erosion / Slope Wash / Gully Erosion – Earth Slide Hazard Scenario Preparatory Causal Factors

Preparatory causal factors recorded for Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide hazard scenarios indicate the slope immediately below the track shows active signs of slope wash, piping, seepage erosion, partial depletion of the track shoulder and ballast sloughing down the slope. All are evidence that these preparatory causal factors are active at the site and this hazard scenario should be identified.

10.6.1.3 Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow Hazard Scenario Preparatory Causal Factors

Preparatory causal factors recorded for Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow hazard scenarios are identified by evidence of slope wash, piping, seepage erosion on the upper slope immediately above the track. In this scenario, potential or evidence of plugged ditches is recorded as an additional preparatory causal factor that can result in the backup of water which can ultimately cause overland or through flow erosion of the track subgrade.

10.6.1.4 Seepage Erosion/ Piping/ Gully Erosion – Earth Slide – Earth Flow Hazard Scenario Preparatory Causal Factors

The two prevalent preparatory causal factors recorded for Seepage Erosion/ Piping/ Gully Erosion – Earth Slide – Earth Flow hazard scenarios include potential or evidence of seepage erosion or plugged ditches.

10.6.1.5 Seepage Erosion / Gully Erosion – Earth Slide – Earth Flow Hazard Scenario Preparatory Causal Factors

Preparatory causal factors recorded for Seepage Erosion / Gully Erosion - Earth Slide Slope wash / gully erosion hazard scenarios are essentially the same as for Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide hazard scenarios with the addition of evidence of beaver habitat and a sloughing shoulder.

10.6.1.6 Seepage Erosion/ Slope Wash / Gully Erosion – Debris Fall Hazard Scenario Preparatory Causal Factors

The two prevalent preparatory causal factors recorded for Seepage Erosion/ Slope Wash / Gully Erosion – Debris Fall hazard scenarios include potential or evidence of slope wash or seepage erosion.

Preparatory Causal Factors: CN Western Canada Railway Ground Hazard Scenarios

Level II Subgroups	Ground Hazard Scenario	Coding	Count	Erosion	Poor Drainage	Beaver Activity	Other Observations
Overland / Through Flow Erosion	**Overland / Through Flow Erosion**						
	Seepage Erosion / Piping / Gully Erosin- Earth Slide / Culvert Failure / Piping Void Collapse	SE / P / GE - ESI - / CF / PD -	50	Piping (10%),Slope (8%),Seepage (8%),Ditch (8%),Stream (8%),Lake (2%),Around Culvert(8%),Inlet (42%),Outlet(28%),	Partially(22%),Blocked(18%),Poor Inlet(14%),PoorOutlet(8%),Ponding or HWT(12%),Rapid Drawdown(2%),Culvert Pulled(4%),Plugged Drains(2%),	Active(18%),Habitat(18%),	Shoulder Sloughing(8%),Ballast Sloughing(8%),Damaged Structure(4%),
	Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide	SE / SW / GE - ESI -	46	Piping (11%),Slope (57%),Seepage (52%),Ditch (2%),Stream (4%),Lake (2%),Inlet (4%),Outlet(2%),	Ponding or HWT(2%),Plugged Ditches(2%),Rapid Drawdown(2%),Anthro(2%),	Active(4%),Habitat(9%),High Gradient(2%),No Buffer(2%),	Shoulder Sloughing(43%),Ballast Sloughing(15%),Damaged Structure(11%),
	Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow	SE / SW / GE - SE / GE / - ESI - EFw -	24	Piping (21%),Slope (21%),Seepage (79%),Ditch (8%),Stream (4%),Inlet (4%),Outlet(4%),	Poor Inlet(4%),Ponding or HWT(13%),Stream Shift(4%),Plugged Ditches(21%),Rapid Drawdown(4%),Anthro(8%),		Ballast Sloughing(4%),
	Seepage Erosion - Earth Slide - Earth Flow	SE - ESI - EFw -	12	Piping (8%),Slope (8%),Seepage (25%),Ditch (8%),	Plugged Ditches(17%),Anthro(8%),	Habitat(8%),	Shoulder Sloughing(8%),Ballast Sloughing(8%),
	Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow	SE / GE - ESI - EFw -	12	Piping (33%),Slope (58%),Seepage (100%),Ditch (8%),Stream (8%),Around Culvert(8%),Inlet (8%),Outlet(8%),	Partially(8%),Blocked(8%),Plugged Ditches(17%),Rapid Drawdown(8%),Anthro(8%),	Active(8%),Habitat(17%),Dam Impound(8%),	Shoulder Sloughing(33%),Ballast Sloughing(8%),
	Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall	SE / SW / GE - DF -	7	Slope (29%),Seepage (57%),			Shoulder Sloughing(14%),Damaged Structure(14%),
		Subtotal	**151**	Piping (13%),Slope (29%),Seepage (43%),Ditch (5%),Stream (5%),Lake (1%),Around Culvert(3%),Inlet (17%),Outlet(11%),	Partially(8%),Blocked(7%),Poor Inlet(5%),PoorOutlet(3%),Ponding or HWT(7%),Plugged Ditches(7%),Rapid Drawdown(3%),Culvert Pulled(1%),Anthro(3%).	Active(8%),Habitat(11%),	Shoulder Sloughing(20%),Ballast Sloughing(9%),Damaged Structure(5%),

Table 10-5 Preparatory causal factors identified for each overland and through flow erosion hazard scenario grouped into erosion, poor drainage, beaver activity and other observations. The percentage each preparatory causal factor was reported for each hazard scenario is presented in brackets.

Table 10-6 Summary of most prevalent preparatory causal factors recorded for each overland/through flow erosion scenario.

Overland/Through Flow Erosion Scenario	#	Prevalent Preparatory Causal Factors Recorded
Seepage Erosion / Piping / Gully Erosion- Earth Slide / Culvert Failure / Piping Void Collapse	50	• erosion around culvert inlets and outlets, • partially or completely blocked culverts, • poor culvert arrangement • beaver habitat
Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide	46	• piping • slope wash • seepage erosion • shoulder and ballast sloughing
Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow	24	• piping • slope wash • seepage erosion • high phreatic surface • plugged ditches
Seepage Erosion - Earth Slide - Earth Flow	12	• seepage erosion • plugged ditches
Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow	12	• piping • slope wash • seepage erosion • plugged ditches • shoulder and ballast sloughing
Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall	7	• slope wash • seepage erosion
Combined	151	• erosion around culvert inlets and outlets, • partially or completely blocked culverts, • poor culvert arrangement • piping • slope wash • seepage erosion • beaver habitat

10.6.2 Suggested Overland / Through Flow Erosion Hazard Event Preparatory Causal Factors

The author's suggested list and descriptions of railway overland / through flow erosion hazard event preparatory causal factors are split into Table 10-7 for overland flow erosion and Table 10-8 for through flow erosion.

Table 10-7 Preliminary railway overland flow erosion hazard preparatory causal factors.

Preparatory Causal Factors – overland flow erosion		Description
1.Ground Conditions		
Ds	Dissolution susceptible rock	The rock properties have to be such that dissolution can occur as a result of overland flow. (limestone, dolomite or gypsum. Associated with karst topography)
ENM	Erodible natural materials	The natural materials passing beneath the rail grade determine the erodibility of the slope either above or below the tracks. Natural materials listed here in increasing order of erodibility: • strong rock (>R2), • weak rock (<R2), • dense till, • coarse colluvium, • dense lacustrine sediments, • coarse sand and gravel alluvium, • fine sand and gravel alluvium, • soft/sensitive sediments or loess
LCA	Large catchment area	Overland flow increases proportional to the catch basin area and thus the overland flow erosion hazards increase with the catchment area.
SS	Steep slopes	Overland flow energy increases exponentially with the slope angle thus the overland flow erosion hazards increase with the slope's angle.
LS	Long slopes	Overland flow volume and energy increases with the length of the slope thus the overland flow erosion hazards increase with the slope's length.
2.Geomorphological Processes		
Dn	Denudation	The process by which a slope is stripped bare of vegitation by the processes of weathering transportation or erosion. Makes the slope more susceptible to overland flow erosion.

Preparatory Causal Factors – overland flow erosion		Description
F	Fires	Removal of the forest cover by fire in the vicinity of the tracks increases the railway slope wash and gullying hazards by: • Decreasing evapotransporation, • Loss of soil suction • Loss of root binding and protection, • Increasing runoff, • Increasing infiltration • Increasing potential of blocked, redirected or concentrated drainage (culverts, ditches, bridges), • Increasing amount of woody debris. These factors result in a increased potential for surface erosion and higher flood volume and peak discharge following rain or snow melt.
SW	Slope wash	As described previously
GE	Gully erosion	As described previously
3.Physical Processes		
LLISM	Low level Intense snow melt	Provides rapid release of surface water increasing the overland flow hazards.
SAR	Significant antecedent rainfall	Provides an abundance of free water saturating the surface soils resulting in near 100% surface runoff greatly increasing overland flow hazards.
IR	Intense rainfall	Provides high rainfall impact forces promoting sheet washing and provides a rapid source of surface water increasing all overland flow hazards.
T	Thawing	Thawing of earth slopes inwards resulting in saturation of surface soils increasing runoff and potential for overland flow hazards.
4.Man-made or Animal Processes		
MmDn	Man-made denudation	The process by which a slope is stripped bare of vegetation by the processes of man. Makes the slope more susceptible to slope wash and gullying hazards by: • Decreasing evapotransporation, • Loss of soil suction • Loss of root binding and protection, • Increasing runoff, • Increasing infiltration • Increasing potential of blocked, redirected or concentrated drainage (roads, paved surfaces, culverts, ditches, bridges),

Preparatory Causal Factors – overland flow erosion		Description
Df	Deforestation	Deforestation in the vicinity of the tracks increases the railway slope wash and gullying hazards by: • Decreasing evapotransporation, • Loss of soil suction • Loss of root binding and protection, • Increasing runoff, • Increasing infiltration • Increasing potential of blocked, redirected or concentrated drainage (haul roads, culverts, ditches, bridges), • Increasing amount of woody debris. These factors result in a increased potential for surface erosion and higher flood volume and peak discharge following rain or snow melt.
BA	Beaver activity	Beaver habitat in the vicinity of the tracks predisposes the track to the processes of beavers increasing the slope wash and gullying hazards by: • Denudation of the slopes, • Increasing the potential flood volume and peak discharge by dam impoundment, • Increasing potential of blocked, redirected or concentrated drainage (culverts, ditches, bridges), • Increasing amount of woody debris or • Increasing likelihood of hydraulic erosion at the toe of the railway embankment.
Ut	Utilities	Leaking utilities such as water, sewer or petroleum product pipelines in or around the track grade represent potential sources of liquid runoff increasing the overland flow hazard.

Table 10-8 Preliminary railway through flow erosion hazard preparatory causal factors.

Preparatory Causal Factors – Through flow erosion		Description
1.Ground Conditions		
Ds	Dissolution susceptible rock	The rock properties have to be such that dissolution can occur because of seepage flow through the rock mass (limestone, dolomite or gypsum. Associated with karst topography)
PSS	Piping susceptible soil	Piping is dependent on the soils gradation, permeability, preferential flow paths, ability to maintain an arched opening, chemical makeup and the erosive nature of the material.
ENM	Erodible natural materials	The natural materials passing beneath the rail grade determine the erodibility of the slope either above or below the tracks. Natural materials listed here in increasing order of erodibility: • strong rock (>R2), • weak rock (<R2), • dense till, • coarse colluvium, • dense lacustrine sediments, • coarse sand and gravel alluvium, • fine sand and gravel alluvium, • soft/sensitive sediments or loess
LCA	Large catchment area	Through flow seepage increases proportional to the catch basin area and thus the through flow erosion hazards increase with the catchment area.
SS	Steep slopes	Hydraulic gradient (and thus the transmissivity) and seepage force increases with the slope angle thus the through flow erosion hazards increase with the slope's angle.
LS	Long slopes	The longer the slope the more likely the phreatic surface will contact the slope surface increasing the seepage erosion hazard..
2.Geomorphological Processes		
SE	Seepage Erosion	As described previously
P	Piping	As described previously
Ds	Dissolution	Erosion of voids in rock developed by solution generally in limestone, dolomite or gypsum. Associated with karst topography

Preparatory Causal Factors – Through flow erosion		Description
Dn	Denudation	The process by which a slope is stripped bare of vegetation by the processes of weathering transportation or erosion. Resulting slope is more susceptible to infiltration of water and thus increases the through flow erosion hazard.
F	Fires	Removal of the forest cover by fire in the vicinity of the tracks increases the potential for groundwater recharge by: • Decreasing evapotransporation, • Loss of soil suction • Increasing infiltration • Increasing potential of blocked, redirected or concentrated drainage (culverts, ditches, bridges), • Increasing amount of woody debris. These factors result in an increased potential for railway through flow erosion hazards.
3.Physical Processes		
LLISM	Low level Intense snow melt	Provides rapid release of water for recharge of the ground water increasing the through flow hazards.
SAR	Significant antecedent rainfall	Provides an abundance of free water saturating the surface soils and provides a sustained recharge of the ground water increasing through flow erosion hazards.
IR	Intense rainfall	Provides a rapid but short duration recharge of the groundwater increasing the through flow hazards. Affect depends on soil permeability and vegetation cover.
F	Frost	Ground frost will have an influence on the groundwater recharge as it acts as a barrier thereby increasing the through flow erosion hazard in its absence. In the discharge area, ground frost can act as an aquitart blocking seepage causing a build-up of seepage pressures that when released during thawing can result in significant seepage erosion.
HGR	High groundwater recharge	Causes a build up of water pressures, a rise in the phreatic surface and an increase in the hydraulic gradient beneath the tracks increasing the seepage erosion and piping hazards.
PW	Ponded water	Ponded water on the uphill side of the tracks, (i.e. due to a blocked ditch or culvert), creates a differential head or hydraulic gradient across the railway embankment increasing the piping and seepage erosion hazards. Hazard depends on the material that makes up the embankment.

Preparatory Causal Factors – Through flow erosion		Description
CE	Culvert erosion	Processes that result in internal hydraulic erosion around a culvert due to: • Water running out of the culvert due to a corrosion or abrasion hole, a pull-apart at a joint or poorly sealed joints, • Soil being sucked in through an opening in the culvert by negative pressure from flowing water in the culvert • Water running along the preferential flow path outside of the culvert driven by a surcharge at the inlet of the culvert due to a backup into the culvert caused by debris or ice blockage at either the inlet or outlet, an under capacity culvert or a buoyancy failure of a surcharged inlet.
4.Man-made or Animal Processes		
MmDn	Man-made denudation	The process by which a slope is stripped bare of vegetation by the processes of man. Makes the slope more susceptible to through flow erosion hazards by: • Decreasing evapotransporation, • Loss of soil suction , • Increasing infiltration • Increasing potential of blocked, redirected or concentrated drainage causing increased groundwater recharge (roads, paved surfaces, culverts, ditches, bridges),
Df	Deforestation	Deforestation in the vicinity of the tracks increases the railway through flow hazards by: • Decreasing evapotransporation, • Loss of soil suction • Increasing infiltration • Increasing potential of blocked, redirected or concentrated drainage causing increased groundwater recharge (haul roads, culverts, ditches, bridges),

Preparatory Causal Factors – Through flow erosion		Description
BA	Beaver activity	Beaver habitat in the vicinity of the tracks predisposes the track to the processes of beavers increasing the through flow hazards by: • Denudation of the slopes, • Increasing ground water recharge by dam impoundment, • Increasing potential of blocked, redirected or concentrated drainage causing increased groundwater recharge and impoundment resulting in an increased hydraulic gradient across railway embankments
BA	Burrowing Animals	Processes and circumstances exist by which voids and preferential flow paths can be formed by burrowing animals such as beavers, bears or ground hogs in or around the track grade resulting in a piping or seepage erosion hazard.
Ut	Utilities	Processes and circumstances exist by which voids and preferential flow paths can be formed by leaking utilities such as water, sewer or petroleum product pipelines in or around the track grade resulting in a piping or seepage erosion hazard.

10.7 Overland / Through Flow Erosion Hazard Scenarios Trigger Causal Factors

10.7.1.1 Observed Overland/Through Flow Erosion Hazard Scenario Trigger Causal Factors

Table 10-9**Error! Reference source not found.** presents the trigger causal factors recorded for each overland/through flow erosion hazard scenario. Table 10-10 provides a summary of the most prevalent trigger causal factors identified for each of the six overland/through flow erosion hazard scenarios. The prevalent recorded trigger causal factors is generally consistent for all six scenarios with intense rain, significant antecedent rain, elevated phreatic surface, snow melt, rapid drawdown and thaw being prevalent in almost all of the scenarios. In all scenarios rain on snow is inferred as an additional trigger causal factor.

A review of these records indicates the predominant common denominator for these hazard scenarios, aside from the presence of fine non-cohesive soil, is the presence or potential for seepage erosion or gully erosion which serves to over-steepen the slope increasing the likelihood of an earth slide. The elevated phreatic surface and higher hydraulic gradient indicated by seepage erosion is an additional causal factor decreasing the slope stability and also increases the potential that the potential earth slide will convert to an earth flow as the saturated slide mass looses its cohesion. Given these preparatory causal factors exist, an incremental increase in any one of them brought on by intense rain, significant antecedent rain, an elevated phreatic surface, snow melt or rapid drawdown could trigger the hazard scenario possibly resulting in track failure.

Level III Subgroups	Ground Hazard Scenario	Coding	Count	Intense Rain	Prolonged Rain	High Water	High Water Table	Piping	Freeze/Thaw	Snow Melt	Raising Freezing Level	Rapid Drawdown	Heavy Snow	Thaw	Anthropogenic	Train Action
Overland / Through Flow Erosion	**Overland / Through Flow Erosion**															
	Seepage Erosion / Piping / Gully Erosin Earth Slide / Culvert Failure / Piping Void Collapse	SE / P / GE - ESl - / CF / PD-	50	66%	46%	12%	62%	20%	2%	58%	2%	24%	0%	6%	2%	6%
	Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide	SE / SW / GE - ESl -	46	63%	50%	11%	67%	4%	11%	67%	0%	46%	0%	28%	4%	4%
	Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow	SE / SW / GE - SE / GE / - ESl - EFw -	24	50%	67%	0%	75%	4%	4%	63%	0%	33%	0%	33%	13%	4%
	Seepage Erosion - Earth Slide - Earth Flow	SE - ESl - EFw -	12	25%	50%	8%	58%	0%	0%	50%	0%	8%	0%	25%	0%	0%
	Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow	SE / GE - ESl - EFw -	12	67%	75%	0%	100%	17%	0%	83%	0%	83%	0%	17%	0%	0%
	Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall	SE / SW / GE - DF -	7	71%	71%	0%	43%	0%	29%	71%	0%	0%	0%	29%	0%	0%
		Subtotal	**151**	**60%**	**54%**	**8%**	**68%**	**10%**	**6%**	**64%**	**1%**	**34%**	**0%**	**21%**	**4%**	**4%**

Table 10-9 Trigger causal factors identified for each overland/through flow erosion hazard scenario identified. The percentage each trigger causal factor was reported for each hazard scenario and each hazard scenario grouping is presented.

Table 10-10 Summary of prevalent overland / through flow erosion hazard trigger causal factors identified according to the functional overland / through flow erosion hazard scenario subgroups.

Overland / Through Flow Erosion Hazard Scenario	Prevalent Trigger Causal Factors Identified	
Seepage Erosion / Piping / Gully Erosion- Earth Slide / Culvert Failure / Piping Void Collapse	• intense rain, • significant antecedent rain • elevated phreatic surface	• piping • snow melt • rapid drawdown • rain on snow*
Seepage Erosion / Slope Wash / Gully Erosion - Earth Slide	• intense rain, • significant antecedent rain • elevated phreatic surface	• snow melt • rapid drawdown • thaw • rain on snow*
Seepage Erosion / Slope Wash / Gully Erosion - Seepage Erosion / Gully Erosion / Earth Slide - Earth Flow	• intense rain, • significant antecedent rain • elevated phreatic surface	• snow melt • rapid drawdown • thaw • rain on snow*
Seepage Erosion - Earth Slide - Earth Flow	• intense rain, • significant antecedent rain • elevated phreatic surface	• snow melt • thaw • rain on snow*
Seepage Erosion / Gully Erosion - Earth Slide - Earth Flow	• intense rain, • significant antecedent rain • elevated phreatic surface	• snow melt • rapid drawdown • thaw • rain on snow*
Seepage Erosion / Slope Wash / Gully Erosion - Debris Fall	• intense rain, • significant antecedent rain • elevated phreatic surface	• freeze thaw • snow melt • thaw • rain on snow*
Combined	• intense rain • significant antecedent rain • elevated phreatic surface	• snow melt • rapid drawdown • thaw • rain on snow*

* Inferred trigger causal factor given that both intense rain and snow melt are identified

10.7.1.2 Suggested Overland / Through Flow Erosion Hazard Event Trigger Causal Factors

The author's suggested list and descriptions of railway overland / through flow erosion hazard event trigger causal factors are split into Table 10-11 for overland flow erosion and Table 10-12 for through flow erosion.

Table 10-11 Suggested railway overland flow erosion hazard trigger causal factors.

Trigger Causal Factors – overland flow Erosion		**Description**
2.Geomorphological Processes		
D	Denudation	The process by which a slope is stripped bare of vegetation by the processes of weathering transportation or erosion. Makes the slope more susceptible overland flow.
F	Fires	Removal of the forest cover by fire in the vicinity of the tracks increases the railway overland flow erosion hazards by: • Decreasing evapotransporation, • Loss of soil suction • Loss of root binding and protection, • Increasing runoff, • Increasing infiltration • Increasing potential of blocked, redirected or concentrated drainage (culverts, ditches, flumes, bridges)
GE	Gully erosion	Gully erosion can trigger subsequent hazard events or track failure by depositing material on the track, retrogressing into the track shoulder, or by overtopping of a railway embankment resulting in catastrophic failure of the rail grade made more severe when there is a sudden release of impounded water comparable to a dam burst scenario.
3.Physical Processes		
LLISM	Low level Intense snow melt	Provides rapid release of surface water triggering the overland flow erosion event.
SAR	Significant antecedent rainfall	Provides an abundance of free water saturating the surface soils resulting in near 100% surface runoff triggering an overland flow erosion hazard.

Trigger Causal Factors – overland flow Erosion		**Description**
IR	Intense rainfall	Provides high rainfall impact forces promoting sheet washing and provides a rapid source of surface water triggering an overland flow erosion event.
RFL	Raising freezing level	Significant rise in the freezing level which can significantly accelerates the snow melt and subsequent overland flow.
T	Thawing	Thawing of earth slopes inwards resulting in reduction in negative pore pressures and saturation in the slope causing an earth landslide hazard.
RD	Rapid draw-down	Elevated pore pressures in the slope lag behind a rapid lowering of the water level and associated removal of the water loading on the slope triggering seepage erosion
RoS	Rain on snow	An inferred trigger causal factor that greatly increases overland flow given that both intense rain and snow melt are identified as triggers. It also typically involves a significant rise in the freezing level which also accelerates the snow melt.
4.Man-made or Animal Processes		
Ir	Irrigation	Increases surface runoff triggering overland flow erosion hazards.
WLU	Water leakage from utilities	Increases surface runoff triggering overland flow erosion hazards.
BD	Blocked drainage	Blockage of culverts, ditches, subdrains or horizontal drains can increase or concentrate surface runoff triggering overland flow erosion hazards.
BDB	Beaver dam burst	A beaver dam burst upstream or downstream of the tracks due to deterioration or inadequate construction of a dam or high flows in the channel can increase surface runoff triggering overland flow erosion hazards..

Table 10-12 Preliminary railway through flow erosion hazard trigger causal factors.

Trigger Causal Factors – Through flow erosion		Description
2.Geomorphological Processes		
SE	Seepage Erosion	As described previously
P	Piping	As described previously

Trigger Causal Factors – Through flow erosion		Description
Ds	Dissolution	Erosion of voids in rock developed by solution generally in limestone, dolomite or gypsum. Associated with karst topography. Incremental dissolution erosion may trigger a through flow erosion event.
3.Physical Processes		
LLISM	Low level Intense snow melt	Provides rapid release of water for recharge of the ground water and possible triggering of a through flow erosion event.
SAR	Significant antecedent rainfall	Provides an abundance of free water saturating the surface soils and provides a sustained recharge of the ground water triggering a through flow erosion event.
IR	Intense rainfall	Provides a rapid but short duration recharge of the groundwater triggering a through flow erosion event.
FT	Frost thawing	In the discharge area, ground frost can act as an aquitart blocking seepage causing a build-up of seepage pressures that when released during thawing can trigger a through flow erosion hazard event.
EPS	Elevated phreatic surface	An incremental rise in the phreatic surface beneath the tracks incrementally decreases suction in the unsaturated zone, introduces positive and possibly excess pore pressures and increases hydraulic gradients in the slope supporting the track.
HGR	High groundwater recharge	Causes a build up of water pressures, a rise in the phreatic surface and an increase in the hydraulic gradient beneath the tracks triggering the seepage erosion or piping failure of the track.
PW	Ponded water	Ponded water on the uphill side of the tracks, (i.e. due to a blocked ditch or culvert), creates a differential head or hydraulic gradient across the railway embankment triggering a seepage or piping erosion hazard event.

Trigger Causal Factors – Through flow erosion		Description
CE	Culvert erosion	Through flow erosion hazard events can be triggered by processes that cause internal hydraulic erosion around a culvert due to: • Water running out of the culvert due to a corrosion or abrasion hole, a pull-apart at a joint or poorly sealed joints, • Soil being sucked in through an opening in the culvert by negative pressure from flowing water in the culvert • Water running along the preferential flow path outside of the culvert driven by a surcharge at the inlet of the culvert due to a backup into the culvert caused by debris or ice blockage at either the inlet or outlet, an under capacity culvert or a buoyancy failure of a surcharged inlet.
4.Man-made or Animal Processes		
BA	Beaver activity	Beaver habitat in the vicinity of the tracks predisposes the track to the processes of beavers increasing the through flow hazards by: • Denudation of the slopes, • Increasing ground water recharge by dam impoundment, • Increasing potential of blocked, redirected or concentrated drainage causing increased groundwater recharge and impoundment resulting in an increased hydraulic gradient across railway embankments
BDB	Beaver dam burst	A beaver dam burst upstream or downstream of the tracks, due to deterioration or inadequate construction of a dam or high flows in the channel, can result in either a sudden impoundment or a sudden draw-down against an embankment. Either way a hydraulic gradient is set up across the embankment or in the draw-down slope that can trigger a seepage erosion hazard event.
BA	Burrowing Animals	If a hydraulic gradient already exists across the embankment, new burrowing up the hydraulic gradient can trigger a piping or seepage erosion hazard event.
Ut	Utilities	If voids or preferential flow paths can be formed by the installation of utilities and if a hydraulic gradient already exists or is created by the installation method, this can trigger a piping or seepage erosion hazard event.

10.8 Attributes for Overland / Through Flow Erosion Scenarios

Table 8-9 lists the overland / through flow erosion events and suggests associated soil types and landform attributes for each of them.

Table 10-13 Description of landform attributes associated with Overland / Through Flow Erosion Hazards

Overland / Through Flow Erosion Hazard	Attribute Description
Slope Wash and Gully erosion	Occurs typically in ML, SC, SM, SP, SW on slopes in the following land forms: fluvial, lacustrine, glacio fluvial, glacio lacustrine, moraine, colluvium, ditch spoils, and anthropogenic cuts and fills. Non vegetated slope areas are predisposed
Seepage Erosion and Piping	Occurs in predominantly homogenous weak earth deposits such as CH, MH, OL, CL and ML commonly found in the following landforms: lacustrine, glacio lacustrine, moraine, ditch spoils anthropogenic cuts and fills.
Dissolution	Erosion of voids in rock developed by solution generally in limestone, dolomite or gypsum. Associated with karst topography

10.9 Overland / Through Flow Erosion Hazard Scenarios Consequence Likelihood Factors

10.9.1 Track Vulnerability

Track vulnerability from overland / through flow erosion hazard scenarios tends to be high due to the difficulty identifying where the hazard scenarios exists and where the track is vulnerable. Overland flow erosion depends on the location and intensity of the climate event that causes the run off and the flow path of the water. Many overland flow events involve an avulsion which makes prediction of where the flow intercepts the tracks difficult. For through flow hazard scenarios difficulty arises from the lack of surface expression until the erosion processes are occurring.

Table 10-14 lists track vulnerability factors corresponding to the mode of track failure and the type of overland / through flow erosion hazard.

Table 10-14 Listing of the track failure attributes corresponding to the modes of track failure and overland / through flow erosion hazard scenarios.

Modes of Track Failure	**Causative Ground Hazards**	**Track Vulnerability Factors**
Removing support from the track structure;	• Gully erosion, • Seepage erosion, piping, dissolution	• Presence of retaining structures or bridges • Size, gradation and compaction of subgrade material. • Shoulder width • Ballast, sub ballast quality • Track drainage

10.9.2 Service Disruption Vulnerability

The service disruption vulnerability factors for overland / through flow erosion hazard scenarios given that track failure has occurred include patrols and inspections, presence or absence of warning devices such slide detector fences or tip over posts, train speed, sight lines, grades, presence or absence of central traffic control circuit in the tracks and traffic frequency. More details on these factors is given in Section 4.6.2.

10.9.3 Derailment Vulnerability

The derailment vulnerability factors for overland / through flow erosion hazard scenarios given that track failure has occurred include patrols and inspections, presence or absence of warning devices such as slide detector fences, train speed, sight lines, grades, presence or absence of central traffic control circuit in the tracks and traffic frequency. More details on these factors is given in Section 4.6.3.

10.10 Summary

From Chapter 3 accidents attributable ultimately to overland / through flow erosion, occurred at a combined frequency of 1.5 per year, severity of $520,000 direct costs per accident accounting for $780,000 per annum occurring mainly on the CN Longlac, Ontario to Winnipeg corridor.

33% of the overland / through flow erosion hazard sites are identified as SE / P / GE - ESI - / CF / PD scenarios which typically involve a culvert which appears to be blocked, damaged, poorly arranged or under sized or there is some indication these processes were active in the past.

30% of the overland / through flow erosion hazard sites are identified as SE / SW / GE – Esl scenarios which typically seepage, slope wash or gully erosion of the lower slope which undermines the shoulder of the track increasing the likelihood of track failure directly or can change the slope geometry such that an earth slide may occur.

16% of the overland / through flow erosion hazard sites are identified as SE / SW / GE - SE / GE / - ESI - EFw which typically involves erosion material generated from seepage, slope wash or gully erosion of an earth slope above the tracks depositing material in the ditch or culvert creating a blockage of flow. The backed up water can either flow over or through the track grade creating the second order seepage erosion, gully erosion or earth slide – earth flow parallel hazards.

8% of the overland / through flow erosion hazard sites are identified as SE - ESI - EFw scenarios which typically involve seepage erosion at the toe of the slope above the tracks due to an elevated phreatic and seepage surface. This combines to create an earth slide hazard which, due to saturation of the non-cohesive earth, will typically convert to an earth flow. The earth flow material ends up on the track causing track failure by blockage.

8% of the overland / through flow erosion hazard sites are identified as SE / GE - ESI - EFw – scenarios which typically involve seepage or gully erosion on the slope below or downstream of the track or seepage or gully erosion from rapid surcharge of one side of an embankment. Failures are commonly triggered by rapid drawdown.

5% of the overland / through flow erosion hazard sites are identified as SE / SW / GE – DF scenarios which essentially involve seepage, slope wash or gully erosion of the finer matrix in a debris slope. The erosion of finer material results in detachment of the larger debris particles causing debris falls.

Slope wash involves soil particles loosened by rainfall or snow melt which flow in sheets or rills, and can initiate gullies. It depends on the magnitude, duration, intensity and frequency of rainfall, the infiltration characteristics of the soil, the length and angle of the slope and the soil surface characteristics.

Gully erosion involves initiation of a channel on a sloping surface with more severe gully erosion events resulting from avulsion or overtopping of embankments. Haul roads, ditches and pre-existing gullies serve to concentrate drainage increasing gully erosion potential. Gully erosion is generally dependent on the factors identified for slope wash events. Excessive erosion in ditches increases the effective slope height and slope angle of cuts and embankments.

Seepage erosion occurs when exit velocity of groundwater is sufficient to cause particle erosion and is typically associated with saturated slopes of erodible materials typically SM or ML. The seepage front typically has an advancing or retrogressive distribution on the slope which can retrogress into the track subgrade. Solifluction is seepage erosion coincident with thawing of surface frost in a fine grained non-cohesive slope.

Piping occurs when water flowing through material opens a tunnel or pipe that remains open and continues to erode material. It is dependent on the soils permeability, preferential flow paths, ability to maintain an arched opening, chemical makeup and the erosive nature of the material. It is typically associated with easily eroded soils, loose backfill around culverts, burrowing rodents, utilities, or buried culverts.

Erosion processes associated with culverts include water running out or into an opening in the culvert, soil being sucked in through an opening in the culvert by negative pressure from flowing water in the culvert, and water running along the preferential flow path outside of the culvert driven by a surcharge at the inlet of the culvert due to a backup into the culvert caused by debris or ice blockage at either the inlet or outlet, an under capacity culvert or a buoyancy failure of a surcharged inlet.

Dissolution involves erosion of voids in rock developed by solution which may progress to a point where the voids undermine the track grade or undermines a slope and occurs in limestone, dolomite or gypsum.

Observed and anticipated rates of track failure from overland / through flow erosion hazards range from slow to rapid depending on the ultimate hazard event befor track failure.

Overland flow events occur relatively quickly after the climatic event and through flow hazard events tend to be incremental with a built in time lag dependent on the permeability, hydraulic gradient and length of flow path. Lag times between hazard events in the overland / through flow erosion scenarios range from days to years which may provide sufficient time for intervention.

As these scenarios are not identified until the preparatory process causal factors are active they would tend to exist in the stable - monitoring required track stability state until mitigated. Triggers such as intense or significant antecedent rain, snow melt or a rise in the phreatic surface may move them to marginally stable.

The prevalent observed preparatory causal factors for the combined overland / through flow erosion scenarios include erosion around culvert inlets and outlets, partially or completely blocked culverts, poor culvert arrangement, beaver habitat and evidence of piping, slope wash or seepage erosion.

Suggested preparatory causal factors for overland flow erosion include:

Ground Conditions:

- Dissolution susceptible rock
- Erodible natural materials
- Large catchment area
- Steep slopes
- Long slopes

Physical Processes

- Low level Intense snow melt
- Significant antecedent rainfall
- Intense rainfall
- Thawing

Geomorphological Processes

- Denudation
- Fires
- Slope wash
- Gully erosion

Man-made or animal processes

- Man-made denudation
- Deforestation
- Beaver activity
- Utilities

Suggested preparatory causal factors for through flow erosion include:

Ground Conditions:

- Dissolution susceptible rock

Geomorphological Processes

- Seepage Erosion

- Piping susceptible soil
- Erodible natural materials
- Large catchment area
- Steep slopes
- Long slopes

Physical Processes

- Low level Intense snow melt
- Significant antecedent rainfall
- Intense rainfall
- Frost
- High groundwater recharge
- Ponded water
- Culvert erosion

- Piping
- Dissolution
- Denudation
- Fires

Man-made or animal processes

- Man-made denudation
- Deforestation
- Beaver activity
- Burrowing Animals
- Utilities

The prevalent recorded trigger causal factors for overland / through flow erosion scenarios include intense rain, significant antecedent rain, elevated phreatic surface, snow melt, rapid drawdown and thaw. In all scenarios rain on snow is inferred as an additional trigger causal factor.

Suggested trigger causal factors for overland flow erosion include:

Geomorphological Processes

- Seepage Erosion
- Piping
- Dissolution

Man-made or animal processes

- Irrigation
- Water leakage from utilities
- Blocked drainage
- Beaver dam burst

Physical Processes

- Low level Intense snow melt
- Significant antecedent rainfall
- Intense rainfall
- Raising freezing level
- Thawing
- Rapid draw-down
- Rain on snow

Suggested trigger causal factors for through flow erosion include:

Geomorphological Processes

- Denudation
- Fires
- Gully erosion

Physical Processes

- Low level Intense snow melt
- Significant antecedent rainfall
- Intense rainfall

Man-made or animal processes

- Beaver activity
- Beaver dam burst
- Burrowing Animals
- Utilities

- Frost thawing
- Elevated phreatic surface
- High groundwater recharge
- Ponded water
- Culvert erosion

The suggested typical soil types and landforms associated with each of the overland / through flow erosion hazards are listed.

Track vulnerability factors specific to the overland / through flow event include presence of retaining structures or bridges, size, gradation and compaction of subgrade material, shoulder width, ballast and sub ballast quality and track drainage.

Service disruption and derailment vulnerability factors include patrols and inspections, presence of warning devices such slide detector fences or tip over posts, train speed, sight lines, grades, presence of central traffic control circuit in the tracks and traffic frequency

Chapter 11 Characterization of Railway Channelized Flow Erosion Hazard Scenarios: CN Western Canada

11.1 Introduction

The third Level III categorization of railway hydraulic erosion hazards is called sub-aqueous flow erosion and includes channelized flow erosion and wave erosion. Channelized flow erosion is defined as erosion of soil particles or rock by channelized flowing water such as streams, rivers and ocean currents. From Chapter 3 there were no train accidents directly attributable to sub-aqueous flow erosion identified in the 1992-2002 records. However, as indicated in Table 10-1, there were significant losses from hazard scenarios which initiated with channelized flow erosion. There were no incidents related to wave erosion in the database and therefore this chapter is limited to channelized flow erosion hazard scenarios only.

Table 11-1 Summary of train accident losses caused from channelized flow hazard events, CN Canada wide 1992-2002

Hydraulic Erosion Hazard Scenarios	**Frequency (events/year)**	**Severity (direct costs/event)**	**Annual Cost (cost/year)**
Channelized Flow Erosion-Earth Landslides	0.91	220,000	**200,000**
Channelized Flow Erosion Erosion-Overland Flow Erosion	0.09	50,000	**4,545**
Combined	**1.0**	**205,000**	**205,000**

The most difficult corridors for channelized flow erosion hazards are in BC where, due to the relief the tracks run along the banks of major rivers.

This chapter steps through the characterization of the identified channelized flow erosion hazard scenarios from the CN Western Canada ground hazard database that would have attributed to these loss records. Following an illustration and description of the hazard scenarios initiating with channelized flow erosion hazard events, the chapter characterizes channelized flow erosion hazard ground conditions and processes, rates and timing of system failure and track stability states. This is followed by identification and characterization of channelized flow erosion events preparatory and trigger causal factors either observed or interpreted by the author followed with an identification of channelized flow erosion revealing factors. The chapter closes with a summary of channelized flow erosion hazard scenarios consequence likelihood factors for track failure, service disruption and derailment.

11.2 Channelized Flow Erosion Hazard Scenarios FMEA's.

The short list of identified hazard scenarios initiating with subaqeous erosion events is presented in Table 8-2. The twelve scenarios identified are further divided into four functional subgroups entitled *Avulsion Upstream of Tracks*, *Channelized Flow Erosion Parallel to Tracks*, *Channelized Flow Erosion Bridge Crossings* and *Wave Erosion*.

Table 11-2 Summary of subsidence hazard scenarios CN Western Canada

Level III	Ground Hazard Scenario	Coding	#
Sub-aqueous Flow Erosion	**Avulsion Upstream of Tracks**		
	Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	Av(BH) - DFw / SE / GE / - ESl - EFw -	441
	Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	Av - DFw / SE / GE / - ESl - EFw -	28
	Subtotal		**469**
	Channelized Flow Erosion Parallel to Tracks		
	Local Scour / Bank Erosion - Earth Slide	LS / BE - ESl -	120
	Bank Erosion - Earth Slide	BE - ESl -	97
	Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide	LS / BE - SW / SE / GE - ESl -	18
	Avulsion - Bank Erosion / Local Scour / General Scour - Earth Slide	Av - BE / LS / GS - ESl	14
	Local Scour / General Scour / Channel Degradation - Earth Slide	LS / GS / ChD - ESl -	7
	Bank Erosion - Rock Slide	BE - RSl -	1
	Subtotal		**257**
	Channelized Flow Erosion Bridge Crossings		

	Channel Agradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion	ChA / DFw - Av - LS / SE / GE -	14
	Local Scour / General Scour / Bank Erosion / Avulsion	LS / GS / BE / Av -	6
	General Scour / Bank Erosion / Avulsion	GS / ChD - ESl -	2
	Subtotal		**22**
	Wave Erosion		
	Wave Erosion - Earth Slide -	WE - ESl -	3
	Subtotal		3
Total Sub-aqueous Flow Erosion Scenario Hazards			**751**

11.2.1 Avulsions Upstream of Tracks

Avulsion upstream of tracks are the most common scenarios dominated by 441 Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow scenarios which is due to the abundance of beaver colonies across Canada and the preparatory causal factors that these animals introduce to drainage systems. The remaining identified hazards in this subgroup are Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow hazard scenarios of which there are 28.

11.2.1.1 Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow

The increasing abundance of beavers in recent years is due to declines in trapping and the reduction in the beaver's natural predators such as wolves and coyotes. Figure 11-1 depicts a simplified FMEA for Avulsion (Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow hazard scenarios. The main preparatory causal factor these hazard scenarios have in common is the presence of beaver habitat. Even if beavers have never been at the site or have abandoned it for some time, the potential that beavers may move in, either upstream or in close proximity on the down stream side due to such conditions as type of vegetation or changes to the water regime gives this site this hazard scenario. These hazards can extend several miles upstream of the tracks and are increased with the steepness of the stream gradients. For the most part the scenarios involve small or ephemeral streams which can run along the track in ditches or cross the track through culverts or small bridges. The avulsion hazard events are typically triggered by intense rainstorms in the watersheds of these small streams providing significant and concentrated flows of water. Beaver dams constructed in parallel in different tributaries or in series in the same tributary cause pre-existing or temporary retentions of the flows which when released by simultaneous dam bursts result in higher than normal peaks and total discharges from the rain event. In many cases, beavers dam the outlet of small lakes raising levels by as much as two or three metres, a significant impoundment volume. The runoff from a lake is instantaneous so these conditions can be particularly hazardous. In addition the presence of beaver habitat introduces the potential for:

- partial or complete blockage of culverts or bridges,
- accumulation of woody debris in the upstream channel,
- impoundment of water behind beaver dams up or down stream of the railway embankment and
- denuding the slopes of trees.

Given that avulsion involves water out of its controlled water course (stream bed, ditches, culverts) the initial hazard that beaver activities create is an avulsion hazard. Assuming an avulsion event has occurred, the second order hazard events include:

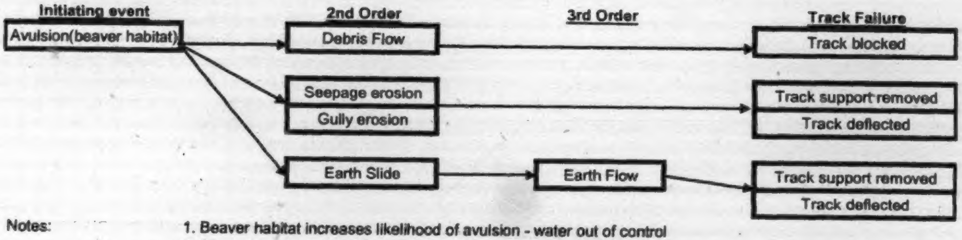
1. A *Debris Flow* event created by erosion and debris entrainment of the newly avulsed water flows. The most likely track failure from this event is track blockage.
2. A *Seepage or Gully Erosion* event as out of control or blocked water flows attempt to pass through or over the railway embankment. A case example of this is given in Figure 11-2 which illustrates the results of a dam burst following an intense rainfall event at Mile 78 of the CN Ft. Francis Subdivision near Fort Francis, Ontario on August 2, 2001 (CN File 4670-FTF-78). On this occasion the beaver dam released by over topping approximately 8 hours after an intense rain storm struck the area. The work train laden with granular material to repair other damage from the storm derailed at the site of this seepage erosion / gully erosion event. The most likely track failure from these events is removal of support from beneath or deflection of the track alignment.

An *Earth Slide – Earth Flow* event resulting from an artificially elevated phreatic surface in the embankment. The earth slide – earth flow can occur on the downstream slope if the elevated phreatic surface reaches it or on the upstream slope due to rapid drawdown caused by removal of culvert blockage for instance. Rapid draw down earth slide – earth flows have been known to occur on the downstream slope due to sudden release of water impounded against the embankment by beaver dams. The Nakina incident which occurred at Mile 133.7 of the Caramat Subdivision near Nakina, Ontario on July 19, 1993 illustrated in

3. Figure 11-3 is a case example of this type of hazard event (CN File 4670-CMT-133.7, TSB, 1992). In this event flows generated by an intense rain event overtopped and failed an abandoned beaver dam which had been impounding water against the railway embankment. The resulting rapid draw down on the embankment triggered an Earth Slide – Earth Flow event which removed the track support and resulted in the derailment and fatalities. The most likely track failure from these events is removal of support from beneath or deflection of the track alignment.

Avulsion Upstream of Tracks Scenarios **Total count: 469**

Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	**Av(BH) - DFw / SE / GE / - ESI - EFw -**	**Count: 441**


Initiating event
Avulsion(beaver habitat)
2nd Order
Debris Flow
Seepage erosion
Gully erosion
Earth Slide
3rd Order
Earth Flow
Track Failure
Track blocked
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. Beaver habitat increases likelihood of avulsion - water out of control
2. Excessive channelized flows can entrain debris starting debris flow
3. Excessive uncontrolled water flows over or through track grade causing grade failure by SE, GE or ESI.
4. Saturated earth slide material looses cohesion and converts to earth flow.

Figure 11-1 Simplified FMEA for Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow hazard scenarios

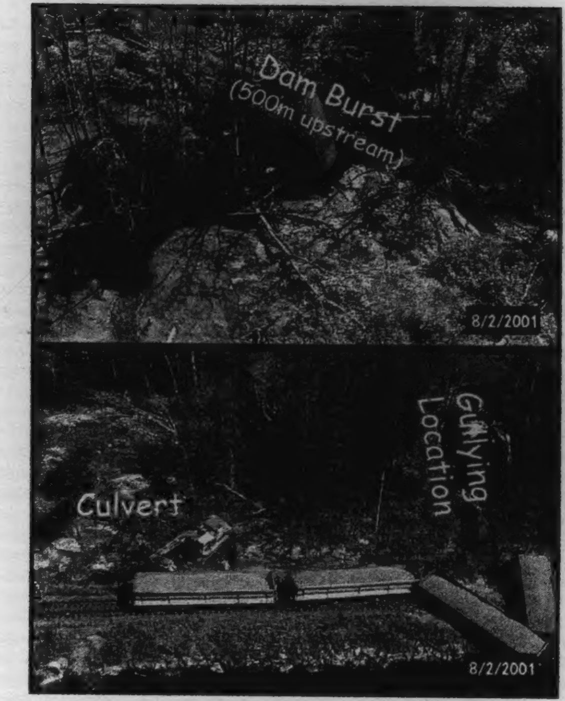

Dam Burst
(500m upstream)
8/2/2001
Gullying
Location
Culvert
8/2/2001

Figure 11-2 Case example of an Avulsion (Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow hazard scenario event which occurred at Mile 78 of CN's Fort Francis Subdivision August 2, 2001 (photos by Tim Keegan; CN file 4670-FTF-78; TSB,1992)

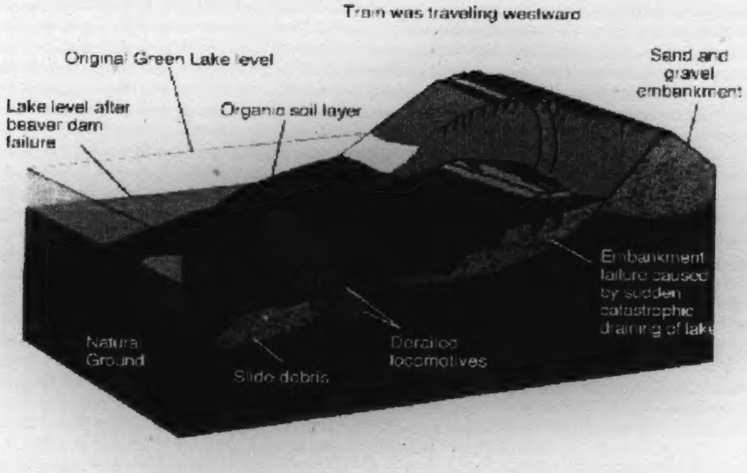

Train was traveling westward
Original Green Lake level
Sand and gravel embankment
Lake level after beaver dam failure
Organic soil layer
Embankment failure caused by sudden catastrophic draining of lake
Natural Ground
Slide debris
Derailed locomotives

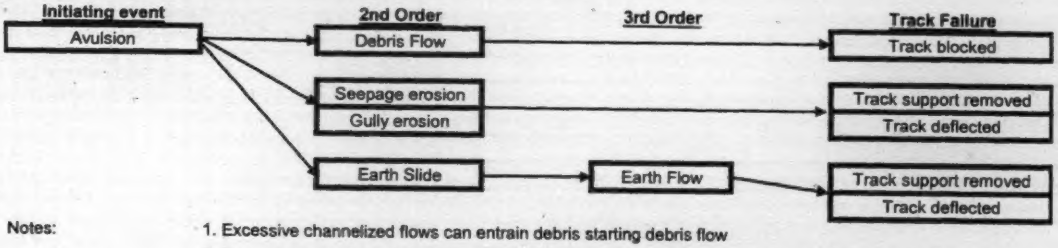
Figure 11-3 Illustration of Nakina derailment at Mile 133.7 of CN's Caramat Subdivision near Nakina, Ontario on July 19, 1993, (CN file 4670-CMT - 133.7)

11.2.1.2 Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow

Figure 11-4 depicts a simplified FMEA for Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow hazard scenarios. This scenario is very similar to Avulsion (Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow hazard scenario except for the lack of beaver habitat. Other preparatory causal factors such as deforestation, parallel drainage patterns, forest fires, logging operations or mature forest cover increase the likelihood of an avulsion hazard event upstream of the tracks. Once the avulsion has occurred, the second and third order hazard events are very similar to those described for Avulsion (beaver habitat) initiated hazard scenarios. The most likely track failure from these events is blockage of the tracks, removal of support from beneath or deflection of the track alignment. Figure 11-5 provides a case example of an Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow hazard scenario which resulted in a major derailment at Mile 85.5 of CN's Albreda Subdivision near Valemount, B.C. on June 17, 1999 (4670-ABD-85.4-85.6). The subsequent investigation by the author revealed that a small ephemeral stream had avulsed approximately 150 metres upslope of the tracks. The avulsed stream eroded a new channel and entrained debris which was subsequently deposited at the inlet of a culvert. The avulsed flows then built up against the railway embankment and failed the track by either seepage erosion from the through flow or gully erosion from the over flow. The flows were generated by late spring snow melt from the mid to upper snow pack and the drainage pattern above the avulsion was parallel down a long uniform slope. A significant amount of deadfall in the mature forest is suggested to be a significant preparatory causal factor for the avulsion as there were logs blocking the channel at the point of avulsion.

Avulsion Upstream of Tracks Scenarios Total count: 469

Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	Av - DFw / SE / GE / ESI - EFw -	Count: 28


Initiating event
2nd Order
3rd Order
Track Failure
Avulsion
Debris Flow
Track blocked
Seepage erosion
Gully erosion
Track support removed
Track deflected
Earth Slide
Earth Flow
Track support removed
Track deflected

Notes:

1. Excessive channelized flows can entrain debris starting debris flow
2. Excessive uncontrolled water flows over or through track grade causing grade failure by SE, GE or ESI.
3. Saturated earth slide material looses cohesion and converts to earth flow.

Figure 11-4 Simplified FMEA for Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow hazard scenarios.

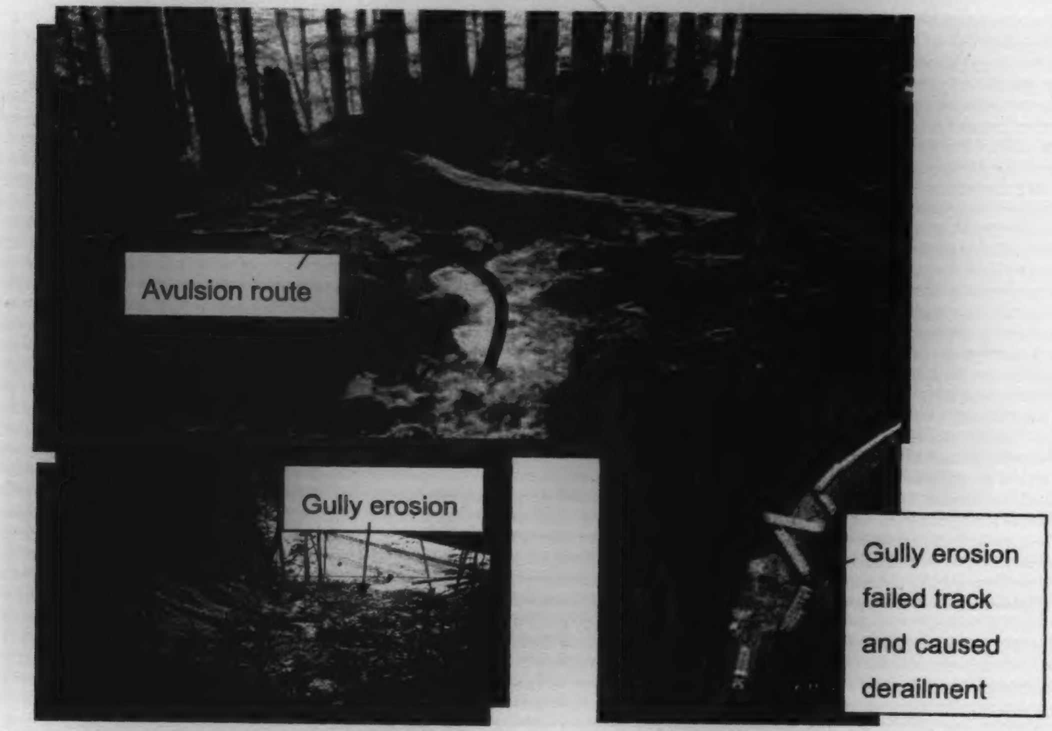

Avulsion route
Gully erosion
Gully erosion failed track and caused derailment

Figure 11-5 Case example of a Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow hazard scenario event at Mile 85.5 of CN's Albreda Subdivision near Valemount, B.C. which occurred on June 17, 1999 (photo by Tim Keegan, CN file 4670-ABD-85.5)

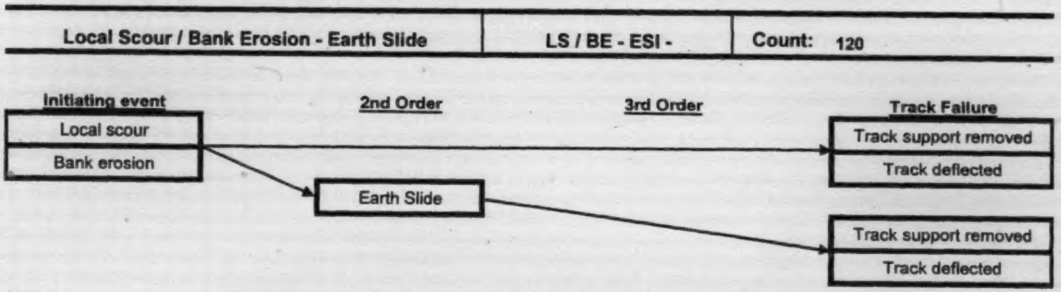
11.2.2 Channelized Flow Erosion Parallel to Tracks

Channelized flow erosion parallel to the tracks refers to situations where the tracks run parallel to the river valley whereas the river channel(s) may flow in a number of different planform patterns such as meandering, anabranching, antisomosing or braided. This is the second most common channelized flow erosion scenario subgroup identified in CN Western Canada due to the majority of the tracks in BC running along the major river valleys. There are six scenarios in this subgroup described below.

11.2.2.1 Local Scour / Bank Erosion - Earth Slide

Figure 11-6 depicts a simplified FMEA for Local Scour / Bank Erosion - Earth Slide hazard scenarios. The common denominator of these scenarios is that they are typically identified where the outside of a meander is in close proximity to the tracks. Local scour events involve localized erosion near the thalweg or base of the channel which may occur during high flows. Bank erosion events involve channelized flow erosion of the bank slope during flood events when the water levels and flows are high on the bank. This erosion may progress to a point where it directly causes the track failure by removing the support from below the track or deflecting the track. In many cases the erosion results in removal of material from the slope supporting the track increasing the likelihood for an earth slide event. The earth slide may occur at the time of the high water or after subsequent removal of the stabilizing water loads during the draw down of the river levels. In some cases the earth slide may not mobilize for a cycle of seasons as in the case of the Local Scour / Bank Erosion - Earth Slide hazard scenario event that occurred at Mile 67.5 of CN's Nechako Subdivision illustrated in Figure 11-7 (CN file 4670-NKO-67.5). This earth slide occurred at the outside meander of the Nechako River in November of 2001 approximately 18 months following the last flood event in June 1999. Surveys indicated the slide toe coincided with a localized scour hole below the river bank and the river level was at its lowest level since the flood event.

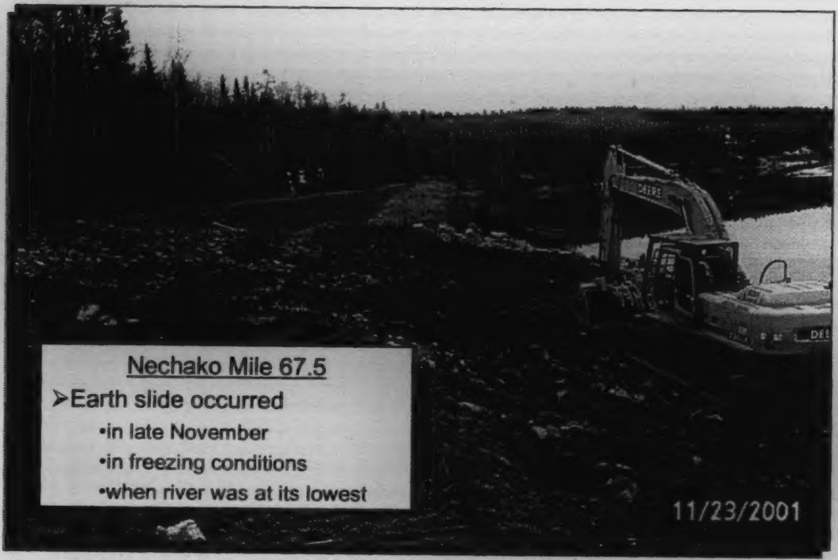
Channelized Flow Erosion Parallel to Tracks Scenarios **Total count: 256**


Local Scour / Bank Erosion - Earth Slide
LS / BE - ESI -
Count: 120
Initiating event
2nd Order
3rd Order
Track Failure
Local scour
Bank erosion
Earth Slide
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. LS at subaqueous toe of slope and BE at mid slope reduce slope stability by changing slope geometry.
2. ESI may not occur until drawdown conditions exist i.e. water level drops

Figure 11-6 Simplified FMEA for Local Scour / Bank Erosion - Earth Slide hazard scenarios



Nechako Mile 67.5

➢Earth slide occurred
- in late November
- in freezing conditions
- when river was at its lowest

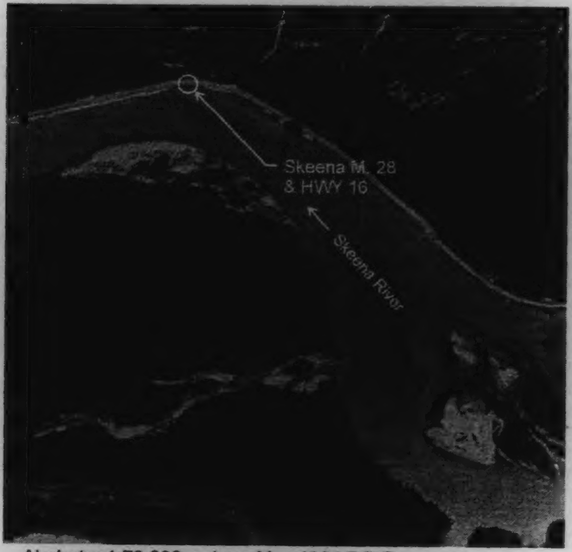
11/23/2001

Figure 11-7 Case example of Local Scour / Bank Erosion - Earth Slide hazard scenario event at Mile 67.5 of CN's Nechako Subdivision. (photo by Tim Keegan, CN file 4670-NKO-67.5)

11.2.2.1.1 Local Scour / Bank Erosion - Earth Slide Hazard Scenario Case Example: Mile 28 Skeena Subdivision

Another case example of this scenario is from Mile 28 of CN's Skeena Subdivision 45 km west of Terrace, BC (Keegan et al, 2003). In this case the chain of hazard events that resulted in track failure in 1999 began several years prior.

The air photograph in Figure 11-8 locates the site in the context of the river. Most of the subdivision follows the right bank of the Skeena River and parallels Highway 16. At Mile 28, CN tracks and Highway 16 are right beside each other occupying the same embankment with CN on the edge of the riverbank. A bedrock knoll bounds the highway on the upslope side.



Airphoto: 1:70,000, colour, May,1994 BC Gov.

Figure 11-8 Skeena Mile 28 location photograph (after Keegan et al, 2003)

This Local Scour / Bank Erosion - Earth Slide hazard scenario involved localized river erosion of cohesionless channel bottom and bank soils, leading to rapid, retrogressive earth-slides of the riverbank. Two such earth slide events occurred in February and July of 2002 with the latter event, depicted in Figure 11-9 (c), undermining the railway grade. On February 20th, 2002, a small earth-slide occurred over a period of a few hours on the riverbank between Miles 28.04 and 28.06 of the Skeena Subdivision. The February failure, a rapid rotational earth-slide, was likely triggered by a rise in soil pore pressures from snowmelt or draw down conditions brought on by a period of low river level following formation of a scour hole. Between the two events CN undertook additional riprap work upstream and downstream of the February slide site. Despite the additional riprap protection, a second failure occurred at or near the same location during the freshet on June 18th, 2002. This time the earth-slide had retrogressed to involve the track grade and the left lane of the highway but had stopped at the ledge in the bedrock surface encountered near the centreline of Highway 16. It is inferred that the second failure was triggered by additional river scour during high flow. The July 18th landslide is classed as a rapid reactivated retrogressive rotational earth-slide.

The bathymetric survey completed in July 2002 and shown in Figure 11-9 (b) indicates the river thalweg was against the north bank, and scour had undermined riprap protection on the bank steepening the lower bank slope. It also indicates that both earth-slide events occurred in the eastern half of the scour hole coincident with the bedrock knoll on the north side of Highway 16 and that slide debris had partially infilled the thalweg at the toe of the earth-slide but scour holes still existed upstream and downstream of the slide.

Scour events during past floods are recognized by the author as the key preparatory causal factor to the earth-slide hazard events.

Figure 11-10 presents one interpretation of the stratigraphy (Keegan et al, 2003) at the site based on a geotechnical investigation conducted following the February failure. The basal rupture surface was likely bounded in a loose sand horizon.

Analysis indicated that a deeper potential rupture surface was marginally stable in a low sensitivity, soft, low plasticity, glacio-marine clay and silt that underlay the granular and loose sand horizons. The Liquid Limit of the silts ranged between 22.8% and 24.9% while the Liquid Limit of the clays ranged between 33.3 and 35.0%.

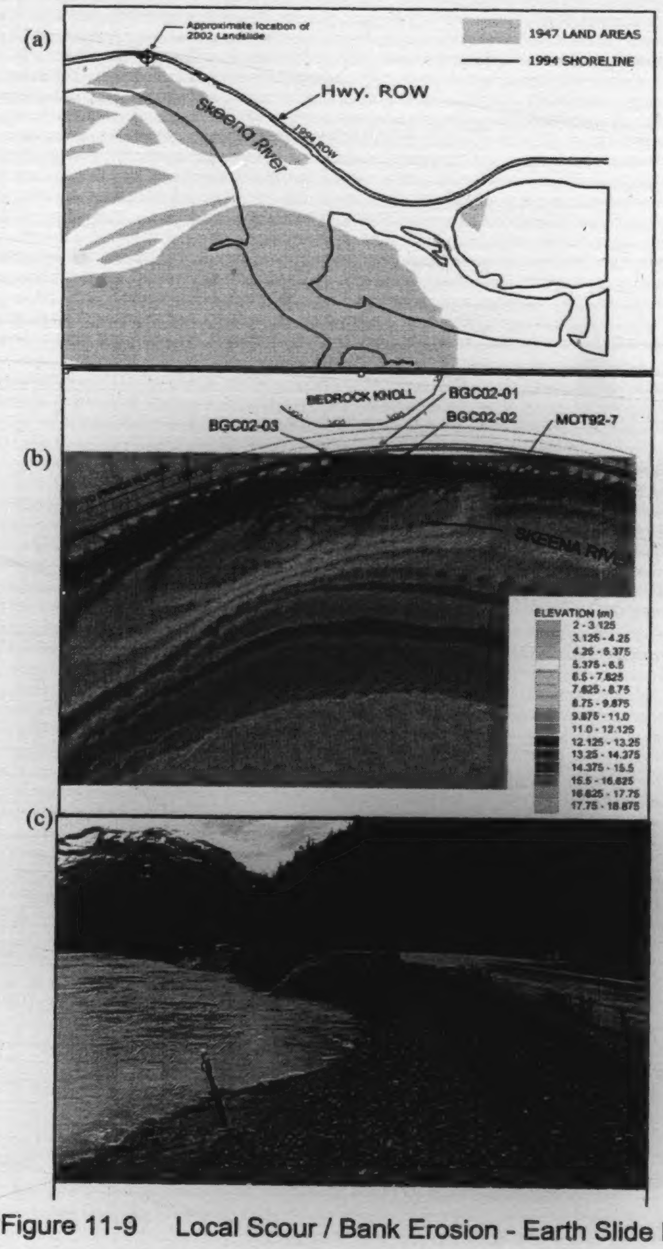

(a)
Approximate location of 2002 Landslide
1947 LAND AREAS
1994 SHORELINE
Hwy. ROW
Skeena River
1994 ROW
(b)
BEDROCK KNOLL
BGC02-01
BGC02-02
BGC02-03
MOT92-7
SKEENA RIV
ELEVATION (m)
2 - 3.125
3.125 - 4.25
4.25 - 5.375
5.375 - 6.5
6.5 - 7.625
7.625 - 8.75
8.75 - 9.875
9.875 - 11.0
11.0 - 12.125
12.125 - 13.25
13.25 - 14.375
14.375 - 15.5
15.5 - 16.625
16.625 - 17.75
17.75 - 18.875
(c)

Figure 11-9 Local Scour / Bank Erosion - Earth Slide hazard scenario event at Mile 28 of CN Skeena Subdivsion, (a) Skeena Mile 28 – Overlay of 1947 and 1994 river locations, (b) Skeena Mile 28 – slope shade image of July 2002 bathymetry, (c) Skeena Mile 28 View looking downstream on July 18, 2002 following the rapid, retrogressive earth slide and track failure. (after Keegan et al, 2003)

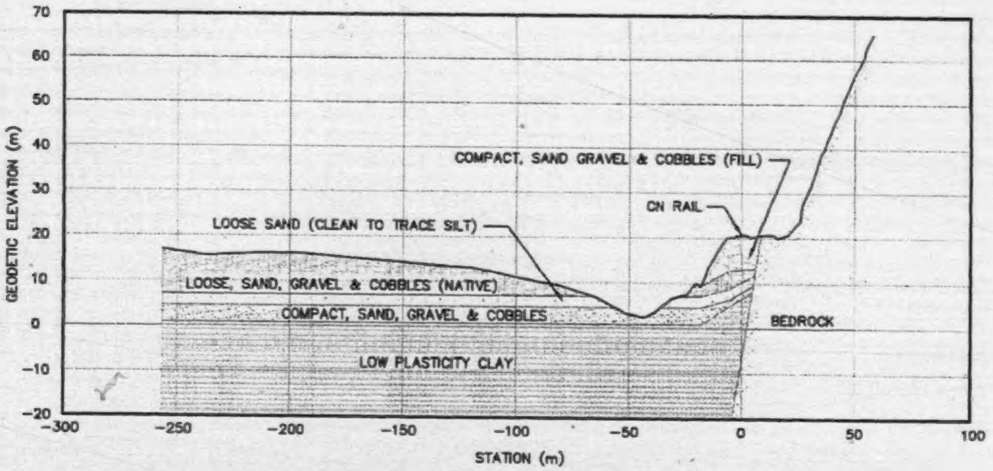


Figure 11-10 Interpreted stratigraphic cross-section looking downstream. (Note: 2:1 vertical exaggeration) (after Keegan et al, 2003)

The Skeena River in proximity to Mile 28 is a braided river. The channel width is generally 500 m, occupying a steep-sided valley with a width of approximately 2 km. Major islands in the river are generally wider than 1.5 km. The channel gradient is measured at 0.57m/km. Anecdotal accounts (personal communication with Mr.David Viveiros, CN Track Supervisor) indicate that extreme floods reach a level approximately 0.3 m above the track at Mile 28 approximately 12m above the thalweg. The bed consists generally of gravel and cobbles. The natural channel banks are generally covered with cobbles and boulders, but have been modified considerably on the right bank by railway and highway construction and maintenance.

Braided implies the river is laterally unstable; channels may be abandoned or reactivated during significant floods. Vertically, the river is generally stable unless recent channel shifts have occurred. This is because sudden flow path changes can lead to dramatic changes in channel gradient, which in turn can lead to bed degradation or aggradation. To investigate this further the temporal changes in the river morphology at the Skeena Mile 28 site were examined (Keegan et al, 2003)

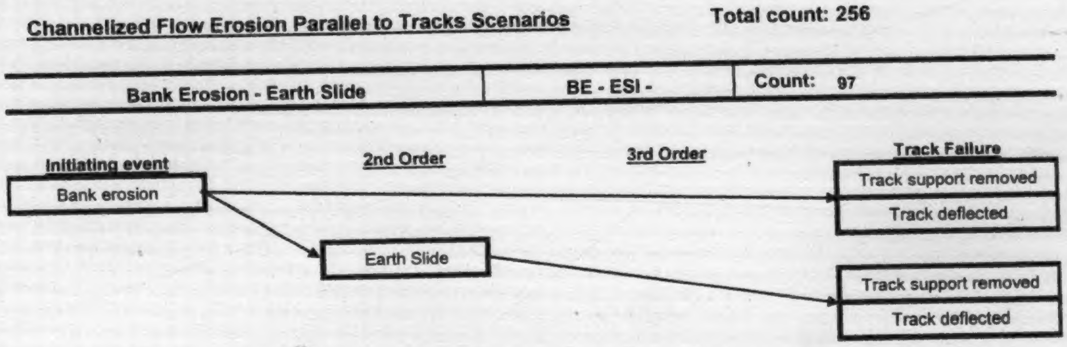
A series of air photographs from 1937 to 1998 were examined to map changes in the river flow patterns and bank position. In 1937, the majority of flow in the Skeena was located on the south side of the valley and did not impact the track. By 1963, the main channel had migrated north until it was against the north bank, although the river curvature was less than is presently the case. Between 1963 and present, the outer edge of the meander migrated downstream and the flow was directed more toward the riverbank as opposed to along it. Figure 11-9 (a) shows an overlay of the 1947 channel location on the 1994 location, illustrating the major shift of the main river channel.

Traces of the river channels from the 1947 and 1994 photographs were overlaid to quantify the bank erosion. This work illustrated that the north bank near Mile 28 has been eroding since 1963 at rates between approximately 0.3 m/yr in the upstream half of the river bend, to 0.75 m/yr at the downstream limit of the bend.

To summarize, the initiating ground hazard event in this scenario was the result of a major stream shift that occurred over a number of years in the braided Skeena River and ultimately resulted in a meander bend directly against the unprotected bank slope supporting the track. These preparatory causal factors created a local scour / bank erosion hazard which was triggered by flood flows in the river. The flood flows occur either from spring snow melt or heavy rains in the water shed. The second order hazard event, which led to track failure, is classed as a reactivated, retrogressive earth-slide. Track failure occurred initially as a track deflection followed by a rapid loss of track support. The interpreted trigger causal factors for this event were either removal of material at the toe or draw down conditions.

11.2.2.2 Bank Erosion - Earth Slide

Figure 11-11 depicts a simplified FMEA for Bank Erosion - Earth Slide hazard scenarios. The common denominator of these scenarios is that the bank slope has been seen to be or is assessed to be prone to bank erosion during high water levels and flows. Typically these sites are identified during or following a flood event when water levels are observed to reach erodible material on the bank. This erosion can either undermine the track support directly or remove the toe material or over steepen the slope creating an earth slide hazard that may subsequently remove the track support. Figure 11-12 illustrates a case example of this scenario at Mile 31.85 of CN's Ashcroft Subdivision where the bank erosion has occurred primarily in the upper portion of the bank slope.


Channelized Flow Erosion Parallel to Tracks Scenarios
Total count: 256
Bank Erosion - Earth Slide
BE - ESI -
Count: 97
Initiating event
2nd Order
3rd Order
Track Failure
Bank erosion
Earth Slide
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. BE at mid slope reduce slope stability by changing slope geometry.
2. ESI may not occur until drawdown conditions exist i.e. water level drops

Figure 11-11 Simplified FMEA for Bank Erosion - Earth Slide hazard scenarios

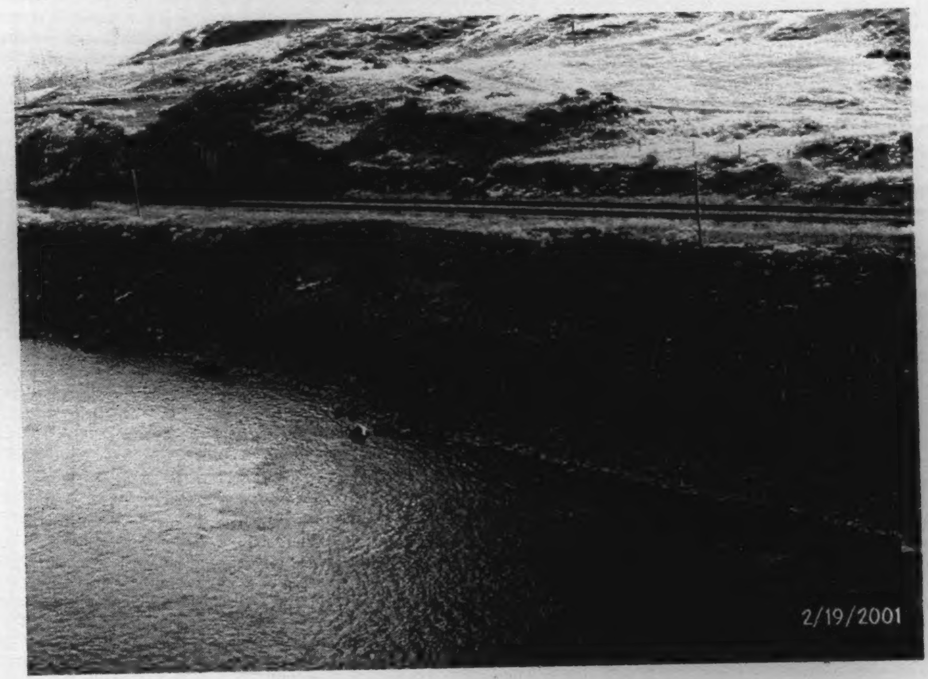


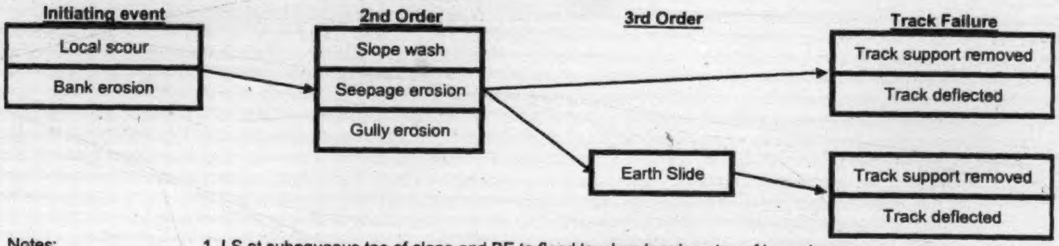
Figure 11-12 Case example of a Bank Erosion - Earth Slide hazard scenario at Mile 31.85 of CN's Ashcroft Subdivision. (photo by Tim Keegan, CN file 4670-ASH-31.85).

11.2.2.3 Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide

Figure 11-13 depicts a simplified FMEA for Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide hazard scenarios. The common arrangement of these scenarios has the track situated above the river level with a long and steep bank slope down to the river. The scenarios initiate with local scour at the channelized toe of the slope or bank erosion up to the river's flood level which serves to over steepen the toe of the long slope. Second order hazard events of slope wash, gully erosion or seepage erosion assist erosion up slope and either remove support from below the track directly or under cut the upper slope creating an earth slide hazard. Both the second and third order hazard events can fail the track by removing support from the track or by deflecting the track.

Of the 18 sites identified as having this scenario, 17 are between Mile 64 and 95 of CN's Ashcroft Subdivision. A number of these sites are between Mile 93 and 95 in what is referred to as the White Canyon and illustrated in Figure 11-14. Within the White Canyon the second order hazard events in this scenario are continuously eroding up to the track shoulder requiring near continuous monitoring and have forced the construction of numerous tie-back retaining walls designed to replace the track support from below.

Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide	**LS / BE - SW / SE / GE - ESI -**	**Count:** 18


Initiating event
Local scour
Bank erosion
2nd Order
Slope wash
Seepage erosion
Gully erosion
3rd Order
Earth Slide
Track Failure
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. LS at subaqueous toe of slope and BE to flood level undermines toe of long slope.
2. Track is relatively high above river such that SW, GE or SE required to progress erosion up slope
3. Potential for ESI increases as slope supporting track starts to be undermined

Figure 11-13 Simplified FMEA for Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide hazard scenarios

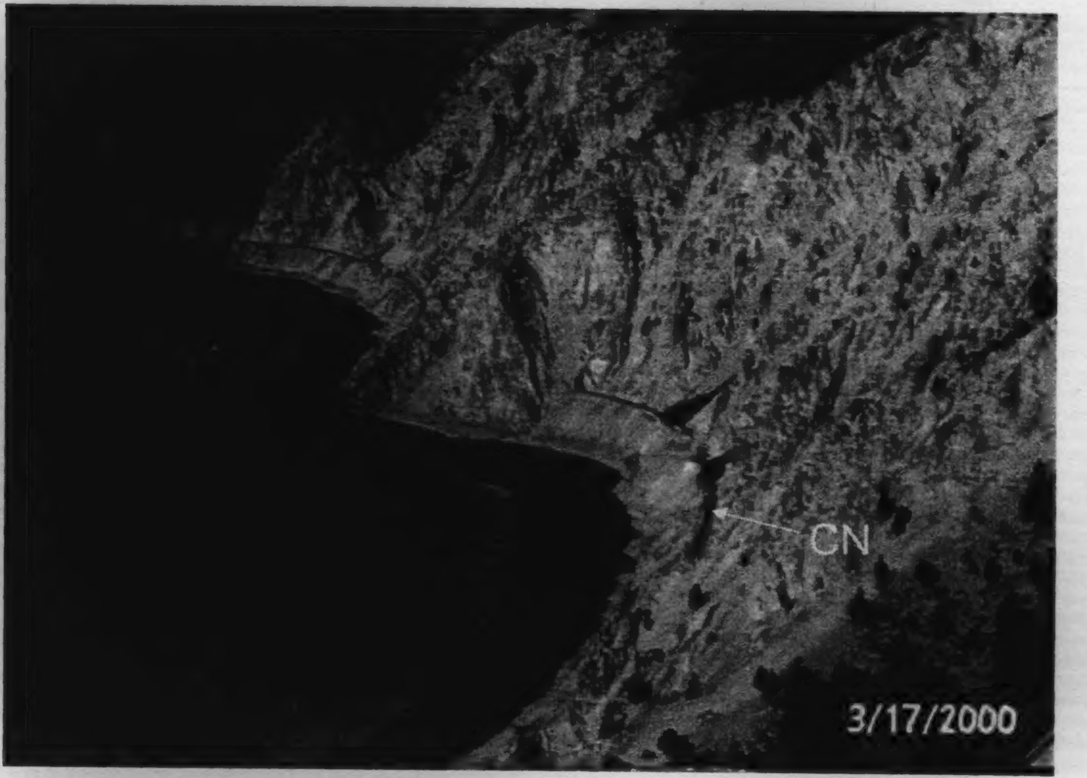


Figure 11-14 South facing (down stream) oblique aerial photo of Mile 93 to 95 of CN's Ashcroft Subdivision, the White Canyon. Location of several Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide hazard scenarios (photo by Tim Keegan)

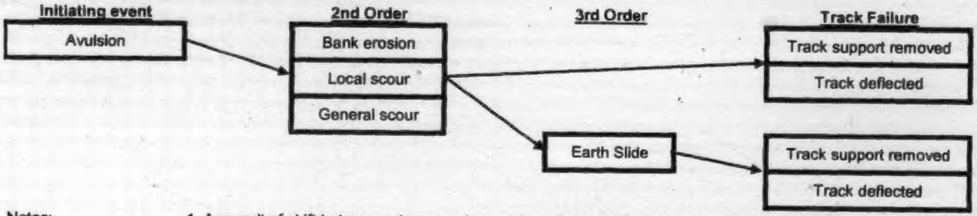
11.2.2.4 Avulsion - Bank Erosion / Local Scour / General Scour - Earth Slide

Figure 11-15 depicts a simplified FMEA for Avulsion - Bank Erosion / Local Scour / General Scour - Earth Slide hazard scenarios. In this scenario the initiating avulsion hazard event involves a shift between the and secondary channels in a multi-channel river, flood flows into a back channel or over bank flows during a flood event. In either case, the scenario requires there to be an increased flow in a channel which flows at the toe of the bank slope supporting the track creating second order bank erosion, local scour or general scour hazards. Any of these three hazard events can erode the toe of the track slope and thus introduce a third order earth slide hazard. All branches of the FMEA can cause track failure by either removing the track support or by deflecting the track.

Figure 11-16 illustrates a case example of an Avulsion - Bank Erosion / Local Scour / General Scour - Earth Slide hazard scenario at Mile 112.1 of CN's Albreda Subdivision whereby a shift in flow from the channel away from the tracks to the secondary channel along the toe of the slope below the tracks resulted in general and possibly local scour which undermined the bank slope resulting in an earth slide. The earth slide failed the track by removing support.

Channelized Flow Erosion Parallel to Tracks Scenarios **Total count: 256**

Avulsion - Bank Erosion / Local Scour / General Scour - Earth Slide	**Av - BE / LS / GS - ESI**	**Count:** 14


Initiating event
Avulsion
2nd Order
Bank erosion
Local scour
General scour
3rd Order
Earth Slide
Track Failure
Track support removed
Track deflected
Track support removed
Track deflected

Notes:

1. Av result of shift between primary and secondary channels, flood flow through back channel or over bank flows.
2. BE, LS & GS resulting in new or increased erosion undermines track slope increasing likelihood of ESI.

Figure 11-15 Simplified FMEA for Avulsion - Bank Erosion / Local Scour / General Scour - Earth Slide hazard scenarios

New primary flow channel
5/5/2003

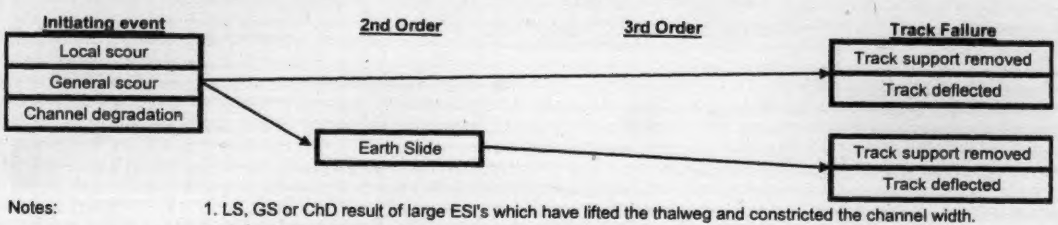
Figure 11-16 Case example of an Avulsion - Bank Erosion / Local Scour / General Scour - Earth Slide hazard scenario at Mile 112.1 of CN's Albreda Subdivision (Aerial photo from Zorkin, (2005), photo by Tim Keegan)

11.2.2.5 Local Scour / General Scour / Channel Degradation - Earth Slide

Figure 11-17 depicts a simplified FMEA for Local Scour / General Scour / Channel Degradation - Earth Slide hazard scenarios. This scenario involves the interplay between post glacial degradation of river systems primarily in BC and the activation and reactivation of large compound retrogressive earth slides.

Channelized Flow Erosion Parallel to Tracks Scenarios **Total count: 256**

Local Scour / General Scour / Channel Degradation Earth Slide	**LS / GS / ChD - ESI -**	**Count:** 7



Notes:

1. LS, GS or ChD result of large ESI's which have lifted the thalweg and constricted the channel width.
2. Erosion at the toe serves to decrease stability of the pre-existing ESI's.

Figure 11-17 Simplified FMEA for the Local Scour / General Scour / Channel Degradation - Earth Slide hazard scenarios

All seven of the sites identified as having this scenario are located between Mile 50 and 57 of CN's Ashcroft Subdivision. There are several large earth-slides located on both banks along this reach of the Thompson River downstream of the Town of Ashcroft (Figure 8-16). The landslides have troubled both CPR and CN since railway construction around the end of the 19th century. The landslides formed as part of the rapid degradation of the Thompson River in post-glacial times through extensive glacial lake deposits that filled the pre-glacial valley (Holland 1976). With the thalweg still well above pre-glacial valley bottom levels over most of its length (NWH, 1977), the local scour, general scour and degradation is expected to continue. As a result, the cyclic interaction between channelized flow erosion and earth-slides is also expected to continue and thus represents an ongoing risk to railway operations.

The initiating ground hazard events in the scenario are local scour, general scour or channel degradation. The trigger causal factors appear to be flood flows in the river that occur in May and June of a flood year. The channelized flow erosion event may result in track failure directly by removing the track support or deflecting the track however it is more likely that these events would serve to undermine the slope creating an earth slide hazard. As discussed in Section 8.3.2.1, erosion at the toe may increase the likelihood of a reactivated, compound earth-slide hazard event which in turn increases the likelihood of a retrogressive, translational earth-slide event if conditions are right. These hazard events are typically triggered by drawdown of the river level in the fall and winter months;

incremental increases in pore pressure brought on by long term antecedent precipitation or irrigation; or intense rainfall filling tension cracks.

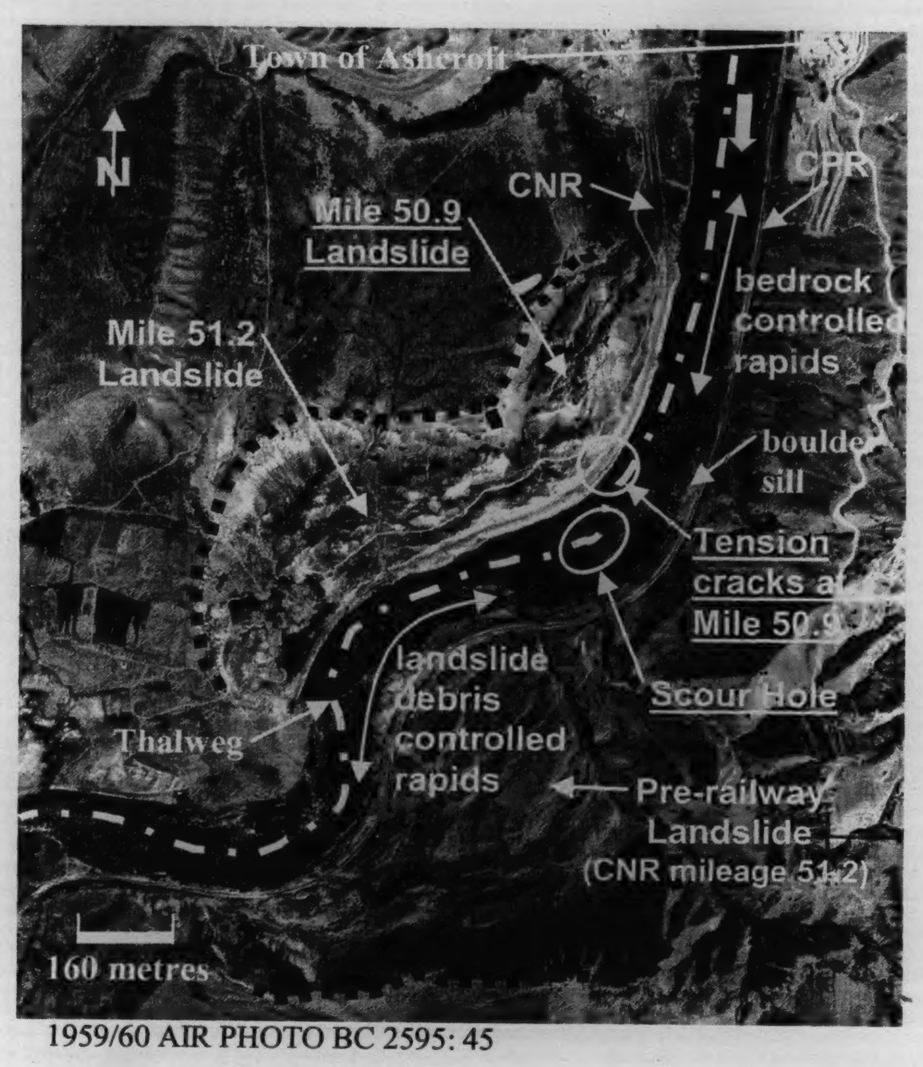
11.2.2.5.1 Local Scour / General Scour / Channel Degradation - Earth Slide Hazard Scenarios Case Example: Mile 50.9 Ashcroft Subdivision

This hazard scenario is documented in the case example taken from Keegan et al, (2003) which describes Mile 50.9 of CN's Ashcroft Subdivision.

Figure 11-18 illustrates the general arrangement of the landslide and river features in the vicinity of the Mile 50.9 Landslide. To understand the river erosion processes in proximity to the Mile 50.9, landslide it is necessary to examine the river morphology.

The river is generally 150 m wide and up to 3 m deep at low stages and 4.5 m or more above low stage level during flood stage (NWH, 1977). The average gradient of the river is 1.4 m/kmm. The bed consists generally of cobbles and boulders overlying gravel, consolidated silt and till, with numerous boulder rapids and some rock outcrops. The natural channel banks are generally covered with cobbles and boulders, but have been modified considerably by landslides and by railway construction and maintenance. The plan-form of the river channel can be described as consisting of irregular entrenched meanders approximately 2.1 kilometres in wavelength. There is no flood plain.

The river is relatively straight in its approach to the Mile 50.9 Landslide, followed by a moderate rightward bend. The toe of the landslide is on the inside of this bend. In these circumstances, it would normally be expected to find the thalweg located adjacent to the left bank whereas, as shown in Figure 11-19, the thalweg is located close to the right bank. The reason for this is apparent from Figure 11-18. Upstream, the rapids are controlled by shallow bedrock on the left bank of the river and, opposite the landslide; the left half of the channel contains a series of boulder bars. This continuous zone of roughened bed on the left side of the channel likely forces flow and the thalweg to the right half of the channel.


Town of Ashcroft
N
CNR
CPR
Mile 50.9 Landslide
Mile 51.2 Landslide
bedrock controlled rapids
boulde sill
Tension cracks a Mile 50.9
Scour Hole
landslide debris controlled rapids
Thalweg
Pre-railway Landslide (CNR mileage 51.2)
160 metres

1959/60 AIR PHOTO BC 2595: 45

Figure 11-18 Location and river hydrology of Mile 50.9 Ashcroft Subdivision earth slide (Keegan et al, 2003)

Immediately downstream of the tension cracks the river appears to have scoured out a 6 metre deep hole towards the middle of the channel (see Figure 11-19). Further downstream, a pre-railway landslide originating from the left bank has evidently pushed the channel significantly to the right and caused the landslide deposit controlled rapids noted on Figure 11-18. It is inferred this secondary translational earth-slide event resulted in a pre-railway landslide dam that flooded a large area upstream. Once breached, the river down cut into the right bank steepening the slope. It is suggested this triggered the activation or reactivation and possible retrogression of the Mile 51.2 and 50.9 compound earth-slides, the first movement type. The 6-metre deep hole in the thalweg immediately downstream of the Mile 50.9 Landslide may be partially a remnant of the channel that existed before the pre-railway landslide.

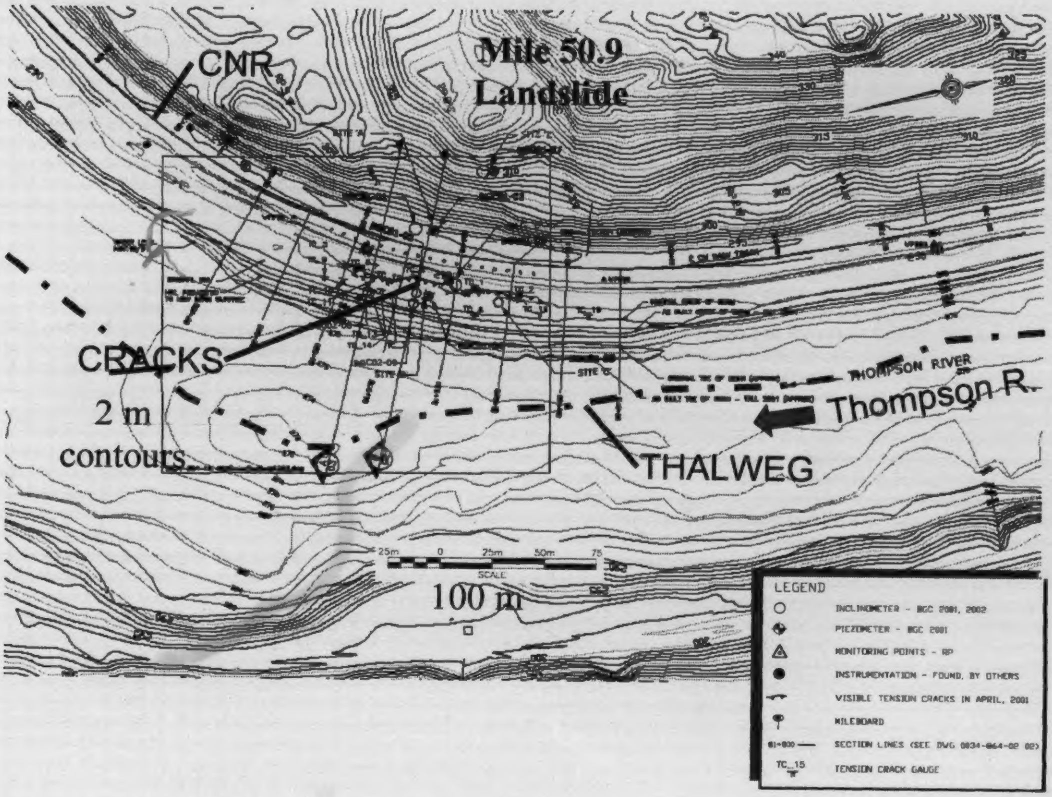

CNR
Mile 50.9
Landslide
CRACKS
2 m
contours
THALWEG
THOMPSON RIVER
Thompson R.
25m 0 25m 50m 75
SCALE
100 m
LEGEND
INCLINOMETER - BGC 2001, 2002
PIEZOMETER - BGC 2001
MONITORING POINTS - RP
INSTRUMENTATION - FOUND. BY OTHERS
VISIBLE TENSION CRACKS IN APRIL, 2001
MILEBOARD
SECTION LINES (SEE DWG 0834-064-02 02)
TC 15
TENSION CRACK GAUGE

Figure 11-19 Bathometric survey of river channel at Mile 50.9 Ashcroft Subdivision earth slide (Keegan et al, 2003)

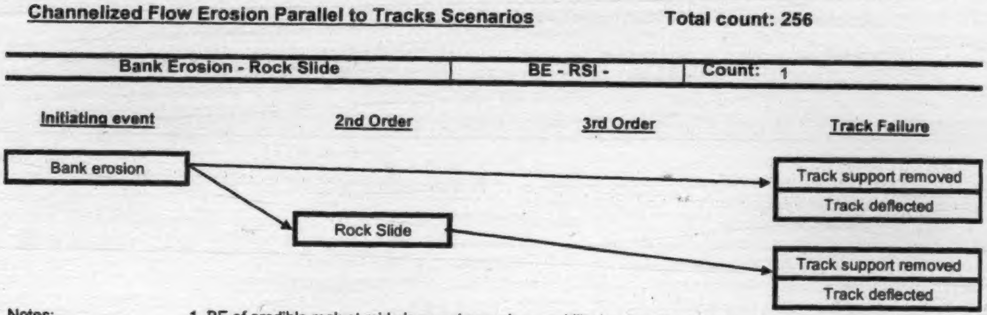
Apparent from the rapids that wrap around the slide deposits of the prehistoric landslide (noted on Figure 11-18) and the 6 metre scour hole upstream of the rapids, the channel is actively degrading into slide deposits which came from both sides of the river and is attempting to reestablish its pre-slide level. This process of channel degradation (Savigny et al, 2002) is expected to continue and thus result in the erosion of material at the toe of the Mile 51.2 and 50.9 landslides. History supports this assessment as movements were observed and remediation required at the location of these landslides in the years following significant flood events most notably the 1921, 1948, 1972, 1997 and 1999 floods. Channel degradation, a ground hazard event, is thus the key preparatory factor to the earth-slide hazards in this case.

Understanding the Local Scour / General Scour / Channel Degradation - Earth Slide hazard scenario at the Mile 50.9 Landslide has enhanced CN's hazard and risk management of this site and others in the following ways:

- A full understanding of the interrelationship between river erosion and earth slides has provided a better understanding of the risk exposure and aided in the realization of the most effective risk control measures.
- Focused attention on the river morphology and the importance of scour protection as a practical means of early intervention.
- Broadened the scope of the investigation and monitoring to include heightened monitoring in the Fall, more extensive and directed installation of piezometers and borehole inclinometers, development and implementation of electric beam level sensors to monitor minor deflections of the track and utilize InSAR (Stewart et al, 2003) technology to detect and measure small ground movements in the 13 kilometre reach occupied by similar landslides.
- Understanding the evolution process of these landslides has provided search criteria used to identify and assess hazard and risk levels of other similar landslides in this reach of the Thompson River.

11.2.2.6 Bank Erosion - Rock Slide

Figure 11-20 depicts a simplified FMEA for Bank Erosion – Rock Slide hazard scenarios. There is only one hazard site identified with this hazard scenario and it is at Mile 80.4 of CN's Aschroft Subdivision. The scenario occurs along the Thompson River where the Drynoch slow debris flow is pushing the river to the right bank. Along this reach, the channel cuts through lightly metamorphosed tuffaceous agglomerate rock which appears to be easily erodible. The channelized flow erosion causes bank erosion of the erodible bedrock on the right bank of the river. Figure 11-21 illustrates the arrangement of the Drynoc landslide relative to the CN tracks and provides a photo to illustrate bank erosion that has forced CN to construct a series of rock sheds (the Skoonka Sheds) and retaining walls to maintain support for their tracks. The second order hazard event is a potential rock slide from under the tracks. All branches of the FMEA can cause track failure by removing support from the track or by deflecting the track.


Channelized Flow Erosion Parallel to Tracks Scenarios
Total count: 256
Bank Erosion - Rock Slide
BE - RSI -
Count: 1
Initiating event
2nd Order
3rd Order
Track Failure
Bank erosion
Rock Slide
Track support removed
Track deflected
Track support removed
Track deflected

Notes: 1. BE of erodible rock at mid slope reduces slope stability by changing slope geometry.
2. Potential RSI from under the track

Figure 11-20 Simplified FMEA for Bank Erosion – Rock Slide hazard scenarios

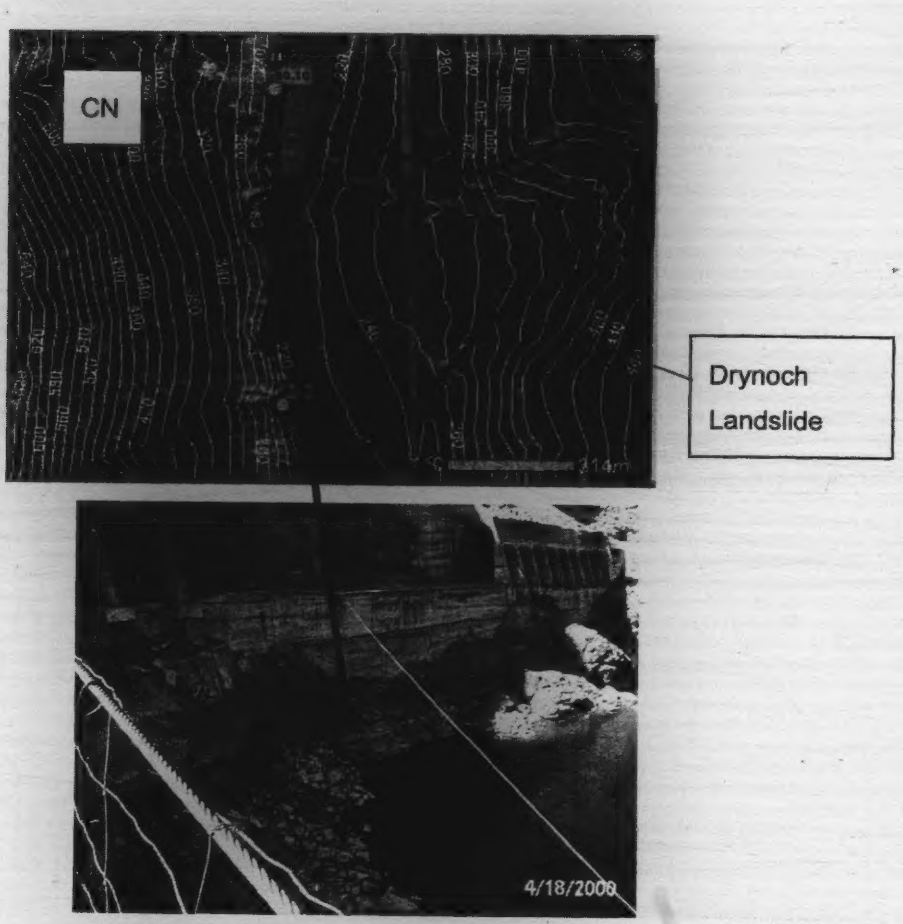


Figure 11-21 Case example of an Bank Erosion – Rock Slide hazard scenario at Mile 80 of CN's Ashcroft Subdivision (Aerial photo from Zorkin, (2005), photo by Tim Keegan)

11.2.3 Channelized Flow Erosion at Bridge Crossings

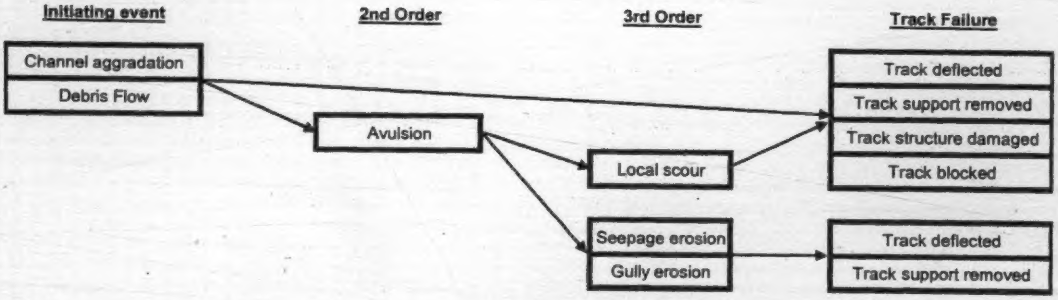
There are 22 hazard sites and three scenarios identified in this subgroup and described in the following sections.

11.2.3.1 Channel Aggradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion

Figure 11-22 depicts a simplified FMEA for Channel Aggradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion hazard scenarios. This scenario typically involves high gradient and high bed load tributary streams that cross the tracks just upstream of their confluence with a major and usually more mature river. The initiating hazard events of channel aggradation and debris flow actually represent two ends of a gradation involving water to solid ratios and particle size distributions as suggested by (insert reference) in Figure (insert figure). Aggradation can also occur from deposition from the main stem river across the mouth of a tributary stream. The initiating events can directly cause track failure by striking the piers, foundations, abutments or spans causing track failure by deflecting the track, removing support from the track, damaging the structure or blocking the track. This branch of the FMEA is illustrated in the case example at Mile 22.4 of CN's Yale Subdivision illustrated in Figure 11-23. In this event a rain on snow trigger causal factor caused a channelized debris flow which filled the channel under the bridge, struck the bridge and deposited debris on the track, failing the track by blockage. In this case the bridge and abutments were not deflected or damaged and the ensuing torrent of water continued to flow under the bridge without causing a local scour hazard event. The second order hazard event is avulsion of the water flows due to partial or complete blockage under the bridge. This can lead to third order hazard events of either local scour of the abutments or piers due to the concentrated and misdirected flows under the bridge or seepage or gully erosion of the track embankment either side of the bridge. Seepage or gully erosion hazard events would fail the track by deflecting or removing support from the track. Figure 11-23 and Figure 11-24 provides two case examples where channel aggradation due to a high bed load is most likely to initiate this scenario.

Channelized Flow Erosion at Bridge Crossing Scenarios **Total count: 22**

Channel Aggradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion	**ChA / DFw - Av - LS / SE / GE -**	**Count:** 14


Initiating event
2nd Order
3rd Order
Track Failure
Channel aggradation
Debris Flow
Avulsion
Local scour
Seepage erosion
Gully erosion
Track deflected
Track support removed
Track structure damaged
Track blocked
Track deflected
Track support removed

Notes:
1. ChA or DFw in tributary streams act to plug bridge clearance causing Av.
2. Blocked, constricted and redirected drainage forces water flow along, over or through track grade.

Figure 11-22 Simplified FMEA for Channel Agradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion hazard scenarios

Figure 11-23 Case example of a Channel Aggradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion hazard scenario involving a debris flow and track failure by blockage at Mile 20.3, CN Yale Subdivision (photos by Tim Keegan Nov 16, 2007, CN file 4670-YLE-20.3)

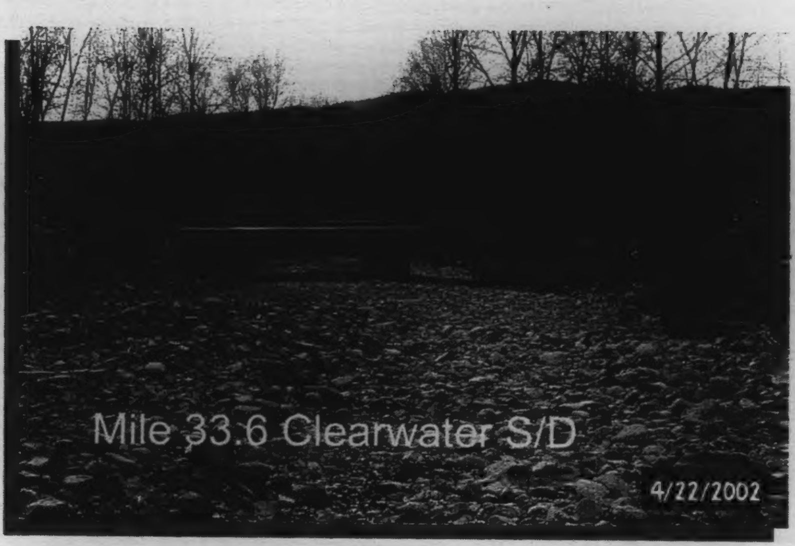
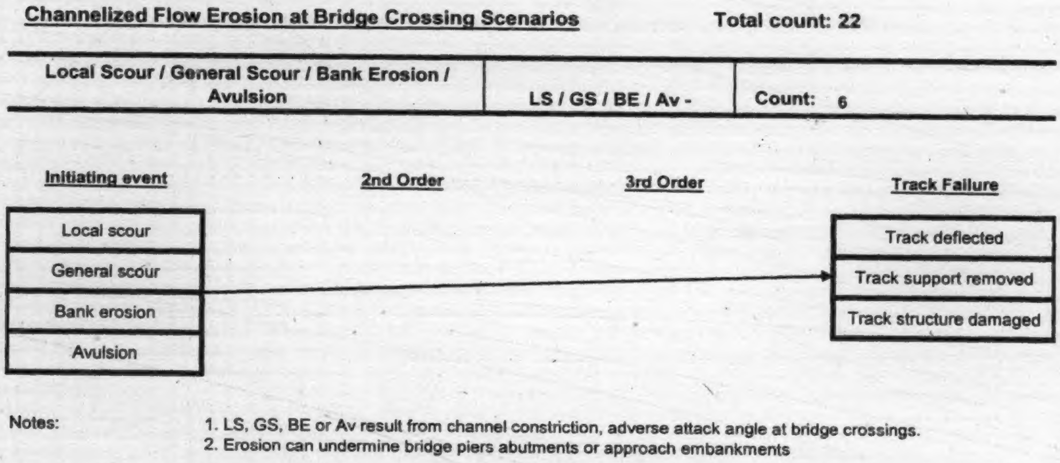


Figure 11-24 Case example of a Channel Aggradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion hazard scenario initiating with an aggradation hazard event at Mile 33.6, CN Clearwater Subdivision (photos by Tim Keegan, CN file 4670-CLR-33.6)

11.2.3.2 Local Scour / General Scour / Bank Erosion / Avulsion

Figure 11-25 depicts a simplified FMEA for Local Scour / General Scour / Bank Erosion / Avulsion hazard scenarios. This scenario typically involves a bridge over a major river where there is an increased likelihood of a local scour of pier or abutment foundations, general scour, bank erosion of the abutment fills or avulsion hazard events that would compromise the bridge in such a way as to cause track failure by deflecting the track, removing support or damaging the support structures. These hazards are usually the result of either a flood event or a change in the river morphological regime. Figure 11-26 presents this type of scenario which developed at Mile 59 of the CN Clearwater Subdivision. In this scenario, a meander cut off channel, an avulsion, in the North Thompson river had formed following a series of flood events in 1997 and 1999. At the time this photo was taken in April 2003, the cut off channel was carrying an estimated 90% of the flow and had caused local scour events at the toe of the approach fill. The local scour hazards were mitigated using riprap berms but the larger concern was from the very poor flow attack angle of the new channel at the bridge. During a flood event this may cause local scour events around and under the abutments and piers due to eddies set up by the poor attack angle and general scour across the channel due to the increased constriction caused by the increased effective width of the piers and to the poor flow attack angle.


Channelized Flow Erosion at Bridge Crossing Scenarios
Total count: 22
Local Scour / General Scour / Bank Erosion / Avulsion
LS / GS / BE / Av -
Count: 6
Initiating event
2nd Order
3rd Order
Track Failure
Local scour
General scour
Bank erosion
Avulsion
Track deflected
Track support removed
Track structure damaged

Notes:
1. LS, GS, BE or Av result from channel constriction, adverse attack angle at bridge crossings.
2. Erosion can undermine bridge piers abutments or approach embankments

Figure 11-25 Simplified FMEA for Local Scour / General Scour / Bank Erosion / Avulsion hazard scenarios

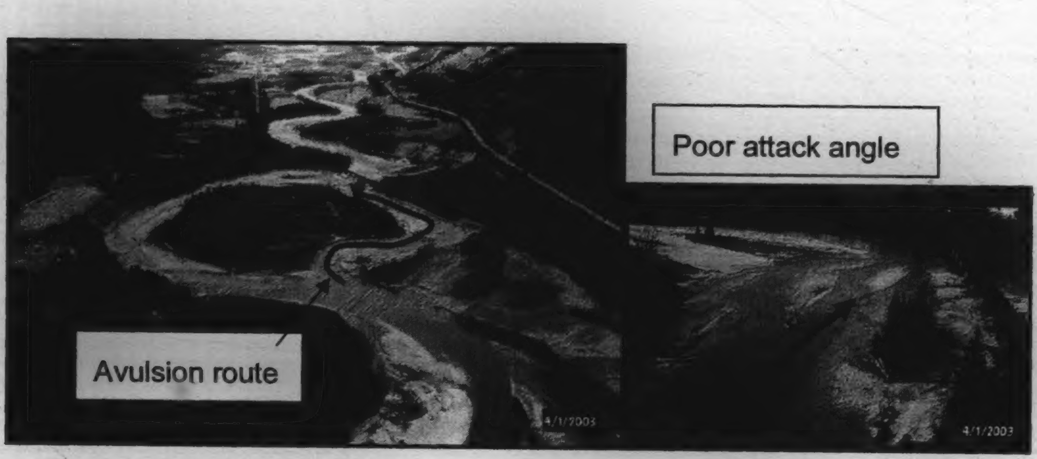
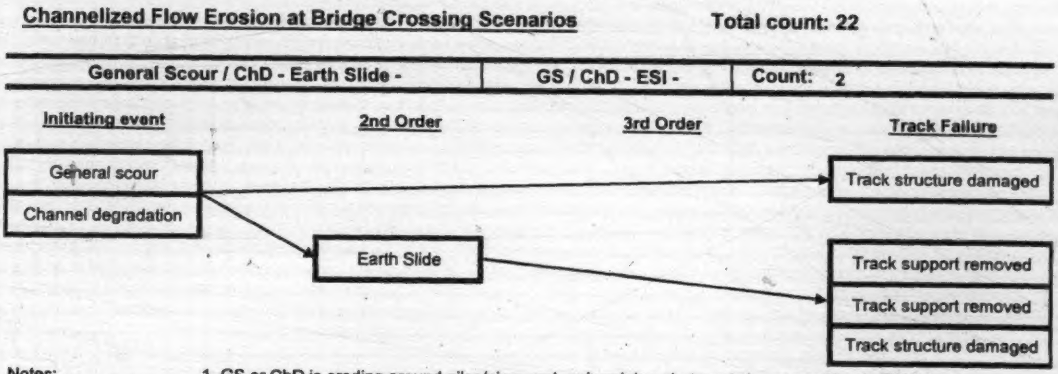

Poor attack angle
Avulsion route
4/1/2003
4/1/2003

Figure 11-26 Case example of a Local Scour / General Scour / Bank Erosion / Avulsion hazard scenario initiating with an avulsion hazard event at Mile 59, CN Clearwater Subdivision (photos by Tim Keegan, CN file 4670-CLR-59)

11.2.3.3 General Scour / Channel Degradation - Earth Slide -

Figure 11-27 depicts a simplified FMEA for General Scour / Channel Degradation – Earth Slide hazard scenarios. This scenario typically involves general scour or channel degradation directly under a railway bridge over a small or even ephemeral stream. The initiating hazard events serve to undermine the toe of one or both abutment slopes. This erosion can either damage the bridge structure causing track failure or cause a second order earth slide event in the abutment slopes which can result in track failure by deflecting the track, removing track support or damaging the bridge.

Figure 11-26 illustrates a case example of this scenario at a bridge at Mile 108.4 of CN's Kinghorn Subdivision. In this case construction of the bridge foundation and footings reduced the effective channel cross-section resulting in an increased general scour hazard. It is possible this stream is also undergoing degradation following the last glaciation. During high flow conditions the channel scoured vertically or laterally, serving to undermine either or both abutment slopes mobilizing earthslides from either bank. The resulting slide movements imposed sufficient lateral loads on the upper pile and pedestals of the adjacent towers to cause mostly horizontal movements as large as 0.6 metres (noted at the south east pedestal of the tower just west of the stream channel). Over the years, CN maintenance crews undertook remedial measures such as shimming and moving the tower footings on the pedestals and encasing the down slope side of the footings with driven sheet piles. Judging from the tilting sheet piles below almost every pedestal; this was only marginally effective.


Channelized Flow Erosion at Bridge Crossing Scenarios
Total count: 22
General Scour / ChD - Earth Slide -
GS / ChD - ESI -
Count: 2
Initiating event
2nd Order
3rd Order
Track Failure
General scour
Channel degradation
Earth Slide
Track structure damaged
Track support removed
Track support removed
Track structure damaged

Notes: 1. GS or ChD is eroding around piles/piers and undermining abutment slopes resulting in ESI hazard.

Figure 11-27 Simplified FMEA for General Scour / Channel Degradation – Earth Slide hazard scenarios

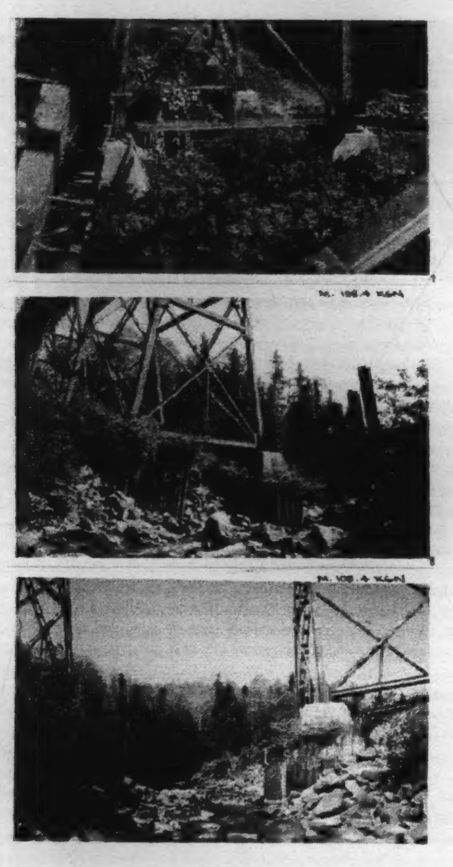
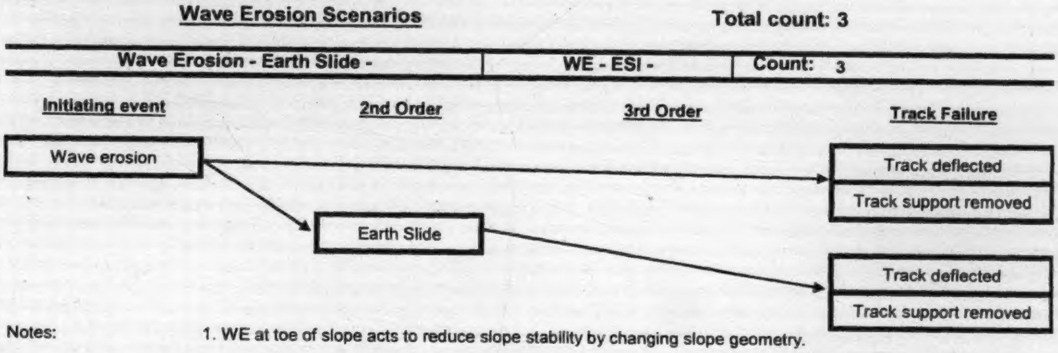


Figure 11-28 Case example of a General Scour / Channel Degradation – Earth Slide hazard scenarios Mile 108.4, CN Kinghorn Subdivision (photos by Tim Keegan, CN file 4670-KGH-108.)

11.2.4 Wave Erosion - Earth Slide -

Figure 11-29 depicts a simplified FMEA for Wave Erosion - Earth Slide hazard scenarios. The three sites identified with this scenario are on the shore of lakes where preparatory causal factors such as evidence of erosion, beach development, a long pitch and predominant wind direction coinciding with a long pitch suggest this hazard scenario exists. Like bank erosion, wave erosion removes material from the toe of the slope supporting the track and can either directly cause track failure or create an earth slide hazard that in turn can cause track failure both by deflecting the track or removing support from the track. Although not identified in the database these scenarios are known to exist along ocean shore fronts along the Skeena Subdivision in which case CN was required to place large size riprap. Ocean wave erosion is known to be more severe due to the additional causal factors of tidal action, ocean storms, very long pitches and particularly tsunamis. In the case of tsunamis, there is the additional second order hazard of gully and seepage erosion.


Wave Erosion Scenarios
Total count: 3
Wave Erosion - Earth Slide -
WE - ESI -
Count: 3
Initiating event
2nd Order
3rd Order
Track Failure
Wave erosion
Earth Slide
Track deflected
Track support removed
Track deflected
Track support removed

Notes: 1. WE at toe of slope acts to reduce slope stability by changing slope geometry.

Figure 11-29 Simplified FMEA for Wave Erosion - Earth Slide hazard scenarios

11.3 Channelized Flow Erosion Hazard Scenarios Ground Conditions and Processes.

This section describes the ground conditions and processes common to channelized flow erosion hazard events. In regions such as British Columbia where the railways are routed along river valleys, channelized flow erosion, has proven to be a railway ground hazard or a significant component of a number of the ground hazard scenarios identified.

In order to minimize both gradient and curvature in high relief terrain railways most often are constructed along the base of river valleys on relatively flat, fluvial terrace or floodplain landforms. As a result, railways commonly parallel the riverbank and are thus frequently affected by fluvial processes such as avulsion, natural scour, degradation or aggradation. When these processes erode the stream bank resulting in steepening or undermining the slope below a railway grade a railway earth landslide hazard is created. Most commonly the resulting track failure is the result of an earth slide although, as interpreted from Ritter et al, (2002, pp. 200), the resulting earth landslide can also occur as a topple or fall.

Channelized flow or river erosion is related to the stream gradient (which determines the flow velocity), soil characteristics of the channel bottom and bank and vegetation. It is also dependent upon orientation and proximity of the channel with respect to the rail grade or any structure, such as bridge, culvert or retaining wall. Most structures or embankments crossing or paralleling a stream affect the stream flow. Structures cause local disturbances in the flow, creating turbulence and increasing channel scour. Local scour frequently develops adjacent to bridge piers, abutments or other asperities along the riverbank. When a structure constricts the channel flow dimensions, most likely to occur when the stream is in flood stage, high velocities are created resulting in concentrated scours at abutments, piers and at the toe of the embankments.

In many cases embankments and bridges impede the natural migration of a streambed. A channel that parallels the grade can erode the streambed, effectively increasing the slope height and angle of the adjoining embankment. Parallel rivers can also erode the banks of their channels and in so doing, erode embankments and/or the foundation for embankments.

Low gradient rivers meander in their valleys, eroding on the outside of the meander and depositing or grading at the inside. Figure 3.10 shows a meandering river/stream that can erode embankments. Erosion at the meander can act to undercut embankments or embankment foundations when the stream is parallel to the grade. When the grade crosses a meandering stream, erosion can undercut abutments or piers. The ground conditions and processes pertaining to the individual channelized flow erosion hazard events are listed and described in the following sections

11.3.1 Channel Aggradation

Aggradation raises the level of the streambed when sediment supply exceeds sediment transport capacity. The aggradation hazard exists when there is an increased likelihood that aggradation can occur and it can lead to burial of a bridge, increased loading on a bridge especially during flooding, bank erosion due to channel widening, increased likelihood of flooding, debris blockage and bridge overtopping. Aggradation is also a leading cause of stream avulsion.

11.3.2 Channel Degradation

Degradation lowers the channel over a reach of a stream or river. Often, in response to a decrease in sediment supply, the down-cutting of an immature river system or down-cutting into landslide material becomes a railway ground hazard if it results in erosion at the toe of a bank slope supporting tracks. Degradation is common in Canadian glaciated terrain as the rivers have not entered their mature stage of development following the last glaciations. Other causes of degradation include down-cutting upstream of a recent meander cut off, down-cutting through landslide debris following a landslide dam and overtopping event and down-cutting responding to isostatic rebound or tectonic uplift.

11.3.3 Local Scour

Local scour deepens a channel by erosion caused by vortexes created by obstructions, increased velocity and downward spiralling currents on the outside bend of a meander or differentially erodible material on the channel bottom. Obstructions can be manmade such as bridge piers or abutments or natural such as bedrock knobs, boulders, gravel bars, or log jams.

11.3.4 General Scour

General scour, also known as constriction scour, locally lowers a channel by reducing the effective width of the channel. Constrictions can be manmade such as rock berms or bridge approach fills, piers and abutments or naturally occurring in the case of alluvial fans, colluvial fans or landslides that encroach and reduce the effective channel width.

11.3.5 Ice jams

Ice jams locally lower a channel due to reduction in the effective depth of the channel caused by excessive build up of ice on the surface. Ice jams often cause local scour, bank erosion, stream avulsion and flooding. Note that damage can also occur to bridges either from impact of the ice or from excessive forces on the bridge caused by the impeded flow.

11.3.6 Log jams

Log jams locally lowering a channel due to reduction in the effective depth of the channel caused by excessive build-up of woody debris on the surface. Log jams often cause local scour, bank erosion, stream avulsion and flooding. Note that damage can also occur to bridges either from impact of the woody debris or from excessive forces on the bridge caused by the impeded flow.

11.3.7 Encroachment

Encroachment shifts the stream bank laterally towards the rail grade. It is associated with meandering stream regimes where the track runs parallel to the stream valley. Encroachment typically leads to local scour and bank erosion of the bank slope supporting the tracks during high flows in the stream.

11.3.8 Bank Erosion

Bank erosion involves localized subaqueous erosion of material from the bank slope. It occurs during high water when unprotected and erodible bank slope material is submerged. Typically this erosion locally undermines the bank slope and the material above the water slides or topples leaving a steepened bank slope. Additional sliding or toppling may occur as the stream level drops due to rapid draw-down conditions. Poorly consolidated silts, sands and gravels erode more than bedrock, cobbles, boulders or cohesive material. Locations on the outside bend of a meander are more susceptible to bank erosion, as velocities are usually greater and flow direction spirals downward.

11.3.9 Avulsion

An avulsion is the escape of a water flow from an original channelized drainage course. A channelized drainage course includes a bank-full channel, ditch, culvert, flume or bridge opening. Avulsion hazard events can be the result of excess flows beyond the capacity of the channelized drainage course, blockage or constriction of the channelized drainage course or a partial or complete shift of flows from one channelized drainage course to another.

These hazard events occur typically in watersheds with hazardous beaver activity, poorly defined or clogged channels, alluvial fans and the floodplains of meandering, anabranching and braided streams. Avulsion upstream of the tracks commonly results in intense erosion and subsequent accretion of sediments potentially blocking culverts or bridges. Beavers block drainage, in ditches and culverts, increase peak flows during flood due to dam breaches, increase the flood flow volume, increase stream bed erosion and contribute debris, primarily woody, to the flood flows. Beavers build dams in water bodies to avoid predators. Beaver dams can be up to a few hundred metres long and a few metres high. These dams are built of twigs, branches of trees and shrubs and soil. Beaver dams fail when water pressures are high or during torrential rains, releasing large amounts of water.

11.4 Channelized Flow Erosion Hazard Scenarios Rates of Ground Hazard System Failure

Table 11-3 presents a summary of the subjectively estimated rates of track failure recorded by the author for the CN Western Canada channelized flow erosion hazard scenarios.

The rates reported for system failure from avulsion up stream of tracks hazard scenarios are predominantly rapid. This is mainly due to the assumption that the avulsion hazard event would release a large volume torrent of water that would result in a rapid failure of the track from a seepage erosion, gully erosion or earth slide – earth flow hazard event.

The rates reported for system failure from channelized flow erosion parallel to the tracks were predominantly moderate to slow. This is due to the ultimate hazard event in the majority of the scenarios, earth slide events, which were assessed to occur at a moderate to slow speed.

The rates reported for system failure from channelized flow erosion at bridge crossings ranged from very slow to very fast. This has to do with the variety of hazard events in these scenarios which would result in the track failure.

Table 11-3 Rates of tracks failure recorded for overland / through flow erosion hazard scenarios

				Percentage of Ground Hazards Reporting this Speed				
Level III Subgroups	Ground Hazard Scenario	Coding	Count	Very Rapid	Rapid	Moderate	Slow	Very Slow
Sub aqueous Flow Erosion	**Avulsion Upstream of Tracks**							
	Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	Av(BH) - DFw / SE / GE / - ESI - EFw -	441	0%	65%	1%	0%	26%
	Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	Av - DFw / SE / GE / - ESI - EFw -	28	0%	14%	36%	11%	4%
		Subtotal	**469**	**0%**	**62%**	**3%**	**1%**	**25%**
	Channelized Flow Erosion Parallel to Tracks							
	Local Scour / Bank Erosion - Earth Slide	LS / BE - ESI -	120	0%	5%	8%	9%	4%
	Bank Erosion - Earth Slide	BE - ESI -	97	0%	8%	29%	16%	2%
	Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide	LS / BE - SW / SE / GE - ESI -	18	0%	11%	61%	6%	0%
	Bank Erosion / Avulsion - Earth Slide	BE / Av - ESI -	14	0%	0%	21%	0%	0%
	Local Scour / General Scour / Channel Degradation - Earth Slide	LS / GS / ChD - ESI -	7	0%	0%	43%	0%	0%
	Bank Erosion - Rock Slide	BE - RSI -	1	100%	0%	0%	0%	0%
		Subtotal	**257**	**0%**	**6%**	**21%**	**11%**	**3%**
	Channelized Flow Erosion Bridge Crossings							
	Channel Agradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion	ChA / DFw - Av - LS / SE / GE -	14	21%	0%	14%	14%	0%
	Local Scour / General Scour / Bank Erosion / Avulsion	LS / GS / BE / Av -	6	0%	17%	0%	0%	0%
	Local Scour / General Scour / Bank Erosion / Avulsion	GS / ChD - ESI -	2	0%	0%	0%	50%	50%
		Subtotal	**22**	**14%**	**5%**	**9%**	**14%**	**5%**
	Wave Erosion							
	Wave Erosion - Earth Slide -	WE - ESI -	3	0%	33%	0%	33%	0%
		Subtotal	**3**	**0%**	**33%**	**0%**	**33%**	**0%**

As for timing within these scenarios, channelized flow erosion events depend on the climate event that provides the source of water flow, rainfall or snow melt, and the return period and magnitude of the specific event and the flow distance from the water source and the hazard site. For example, avulsions a short distance upstream of the track affect the track soon after the avulsion whereas channelized flow erosion parallel to the tracks occurs mostly in major rivers where the source water, upper tributaries and upper snow pack are long distances from the hazard site.

The most notable lag time between hazard events in these scenarios is between the toe erosion from channelized flows and the activation or reactivation of an earth slide. The earth slide may occur at the time of the high water or after subsequent removal of the stabilizing water loads during the draw-down of the river levels. In some cases the earth slide may not mobilize for a cycle of seasons.

11.5 Channelized Flow Erosion Hazard Scenarios Track Stability States.

Because the common preparatory causal factor processes stem from flowing water in close proximity to the tracks and these are not likely to go away, the majority of the channelized flow erosion hazards remain, as a minimum, in the *preparatory activity stage* (see Table 4-5). In addition, since most of the channelized flow erosion hazards can directly fail the tracks, this preparatory activity stage translates to a (3) *Stable – monitoring required* track stability state.

11.6 Channelized Flow Erosion Hazard Scenarios Preparatory Causal Factors

11.6.1 Observed Channelized Flow Erosion Hazard Scenario Preparatory Causal Factors

Error! Reference source not found. presents the preparatory causal factors identified for each channelized flow erosion hazard scenario. A summary of the more prevalent preparatory causal factors recorded for each channelized flow erosion scenario is listed in Table 10-6.

Level III Subgroups	Ground Hazard Scenario	Count	Erosion	Poor Drainage	Beaver Activity	Other Observations
Sub aqueous Flow Erosion	**Avulsion Upstream of Tracks**					
	Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	441	Seepage (2%),Inlet (10%),Outlet(66%),	Partially(1%),Blocked(3%),Ponding or HWT (3%),Plugged Ditches (13%),Rapid Drawdown (66%),	Active (63%),Habitat(97%),Dam Impound(1%),No Buffer(1%),	
	Avulsion - Debris Flow /Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	28	Piping (7%),Slope (32%),Seepage (7%),Ditch (11%),Stream (29%),Bridge (4%),Inlet (14%),Outlet(4%),River(11%).	Partially(4%),Blocked(4%),Poor Inlet(7%),Marshes (4%),Stream Silt(54%),New Stream (7%),Plugged Ditches (11%),[illegible](7%).	Active (4%),Habitat(4%).	Boulder Sloughing(11%),Ballast Sloughing(11%).
	Subtotal	469	Slope (3%),Seepage (2%),Ditch (1%),Stream (2%),Inlet (67%),Outlet(62%).	Partially(1%),Blocked(3%),Poor Inlet(1%),Ponding or HWT (3%),Stream Silt(3%),Plugged Ditches (13%),Rapid Drawdown (61%).	Active (60%),Habitat(91%),Dam Impound(1%),No Buffer(1%).	
	Channelized Flow Erosion Parallel to Tracks					
	Local Scour / Bank Erosion - Earth Slide	120	Slope (3%),Seepage (2%),Stream (53%),River(55%).	Stream Silt(3%),Plugged Ditches(2%).	Active (2%),Habitat(2%).	Boulder Sloughing(8%),Ballast Sloughing(4%).
	Bank Erosion - Earth Slide	97	Slope (10%),Seepage (1%),Ditch (1%),Stream (89%),Bridge (3%),Inlet (1%),River(91%).	Stream Silt(6%),Plugged Ditches (1%),[illegible](2%).	Active (1%),Habitat(1%).	Boulder Sloughing(14%),Ballast Sloughing(3%),Damaged Structure (1%),Cuttings Sloughing(1%).
	Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide	10	Slope (60%),Seepage (6%),Stream (89%),River(89%).			Boulder Sloughing(44%),Ballast Sloughing(17%),Cuttings Sloughing(6%).
	Bank Erosion / Avulsion - Earth Slide	14	Slope (7%),Stream (86%),Bridge (14%),River(64%).	Stream Silt(64%),[illegible](7%).		
	Local Scour / General Scour / Channel Degradation - Earth Slide	7	Stream (100%),River(100%).			Boulder Sloughing(43%),Ballast Sloughing(14%).
	Bank Erosion - Rock Slide	1	Slope (100%),Stream (100%),River(100%).			Damaged Structure (100%).
	Subtotal	257	Slope (10%),Seepage (3%),Stream (72%),Bridge (2%),River(79%).	Stream Silt(7%),Plugged Ditches (1%),[illegible](1%).	Active (1%).	Boulder Sloughing(13%),Ballast Sloughing(5%),Cuttings Sloughing(1%).
	Channelized Flow Erosion Bridge Crossings					
	Channel Agradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion	14	Bridge (57%),Inlet (7%).	Blocked(7%),Stream Silt(36%).		
	Local Scour / General Scour / Bank Erosion / Avulsion	6	Stream (17%),Bridge (83%),River(17%).	Stream Silt(17%).	Habitat(17%),No Buffer(17%).	
	General Scour / Channel Degradation - Earth Slide	2	Stream (100%),Bridge (100%),River(100%).			
	Subtotal	22	Stream (14%),Bridge (68%),Inlet (5%),River(14%).	Blocked(5%),Stream Silt(27%).	Habitat(5%),No Buffer(5%).	
	Wave Erosion					
	Wave Erosion - Earth Slide -	3	Lake (100%).			Boulder Sloughing(33%).
	Subtotal	3	Lake (100%).			Boulder Sloughing(33%).

Table 11-4 Preparatory causal factors identified for each channelized flow erosion hazard scenario grouped into erosion, poor drainage, beaver activity and other observations. The percentage each preparatory causal factor was reported for each hazard scenario is presented in brackets.

Table 11-5 Summary of most prevalent preparatory causal factors recorded for each channelized flow erosion scenario.

Sub-aqueous flow erosion hazard scenario	#	Prevalent Preparatory Causal Factors Recorded
Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	441	• erosion around culvert inlets and outlets • susceptible to rapid drawdown • active beavers • beaver habitat
Avulsion - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	28	• slope erosion • stream erosion • prone to stream shift
Local Scour / Bank Erosion - Earth Slide	120	• stream and river erosion
Bank Erosion - Earth Slide	97	• stream and river erosion
Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide	18	• stream erosion • shoulder sloughing
Avulsion - Bank Erosion / Local Scour / General Scour - Earth Slide	14	• stream erosion • prone to stream shift
Local Scour / General Scour / Channel Degradation - Earth Slide	7	• stream and river erosion • shoulder sloughing
Bank Erosion - Rock Slide	1	• stream and river erosion • damaged structure
Channel Aggradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion	14	• bridge • prone to stream shift
Local Scour / General Scour / Bank Erosion / Avulsion	6	• bridge
General Scour / Bank Erosion / Avulsion	2	• stream and river erosion
Wave Erosion - Earth Slide -	3	• Lake

From his study of regional slope stability controls and related engineering geology of the Fraser Canyon, B.C. Piteau (1976) concluded that alluvial fan and river directional changes are the most significant preparatory causal factors which had caused slope instability problems on a regional basis. His study indicated that 66% of incidents of rockfalls and other slope failures recorded along CN occurred opposite alluvial fans and 33% occurred opposite river directional changes. Also of significance for this reach of the Fraser River was the strong correlation between mapped post glacial landslides and lateral river erosion.

11.6.2 Suggested Channelized Flow Erosion Hazard Event Preparatory Causal Factors

The author's suggested list and descriptions of railway channelized flow erosion hazard event preparatory causal factors are presented in Table 10-7. The concern with channelized flow erosion processes is mainly that they act to remove the toe of the slope effectively steepening and destabilizing the slope. Therefore the main preparatory causal factors for these hazards are a stream or river in close proximity, there is some evidence of channelized erosion, the plan geometry or river morphology of the stream is such that stream erosion is assessed to be likely at that location. The deflection of the river into the opposite bank results in extensive steepening and undermining of the canyon wall slope due to severe lateral erosion.

The other preparatory causal factor inferred at these sites is the buildup of the phreatic surface in the embankments during sustained high water levels, which can lead to destabilizing draw down conditions in the slope. Coupled with changed geometry caused by toe erosion, these can bring the slope to failure following a rapid drop in the water level.

Table 11-6 Suggested railway Sub-aqueous flow erosion hazard preparatory causal factors.

Preparatory Causal Factors – Channelized Flow Erosion		Description
1.Ground Conditions		
ES	Erodible soils	Poorly consolidated silts, sands and gravels
Ds	Dissolution susceptible rock	The rock properties have to be such that dissolution can occur because of seepage flow through the rock (limestone, dolomite or gypsum. Associated with karst topography)
PSS	Piping susceptible soil	Piping is dependent on the soils gradation, permeability, preferential flow paths, ability to maintain an arched opening, chemical makeup and the erosive nature of the material.

Preparatory Causal Factors – Channelized Flow Erosion		Description
Ds	Dissolution susceptible rock	The rock properties have to be such that dissolution can occur. (limestone, dolomite or gypsum. Associated with karst topography)
ENM	Erodible natural materials	The natural materials in the stream bank, streambed or beach determine the erodibility of the track embankment and thus the channelized flow erosion hazard to the tracks. Natural materials listed here in ascending order of erodibility: • strong rock (>R2), • weak rock (<R2), • dense till, • coarse colluvium, • dense lacustrine sediments, • coarse sand and gravel alluvium, • fine sand and gravel alluvium, • soft/sensitive sediments or loess
Cc	Channel confinement	Incorporates valley setting, floodplain development, and entrenchment
Wd	Narrow Effective Stream Width	Measure of the channel constriction at bridges, landslides, alluvial fans or other obstructions (influences depth of local and general scour and rate and height of bank erosion)
LWS	Large water shed	Stream flow and the variability of stream flows increases proportional with the water shed area and thus so do the channelized flow erosion hazards.
SG	Steep gradient	Flow rates and erosion forces increase with the stream gradient thus so do the channelized flow erosion hazards.
PFG	Plane form geometry	The various factors used to describe the plane form geometry of the stream are preparatory causal factors.
Age	Relative age	The relative age of the stream towards maturity

Preparatory Causal Factors – Channelized Flow Erosion		Description
2.Geomorphological Processes		
ChA	Channel Aggradation	As described previously in Section 11.3.1
ChD	Channel Degradation	As described previously in Section 11.3.2
LS	Local Scour	As described previously in Section 11.3.3
GS	General Scour	As described previously in Section 11.3.4
Ij	Ice jams	As described previously in Section 11.3.5
Lj	log jams	As described previously in Section 11.3.6
En	Encroachment	As described previously in Section 11.3.7
BE	Bank Erosion	As described previously in Section 11.3.8
Av	Avulsion	As described previously in Section 11.3.9
LdSl	Landslides (constricting channel)	Landslide constricting the channel upstream, downstream or at the site. Changing sediment supply and promoting aggradation, degradation, and avulsion.

Preparatory Causal Factors – Channelized Flow Erosion		Description
AF	Alluvial Fans	Alluvial fans constricting the channel upstream, downstream or at the site. Changing sediment supply and promoting lateral erosion, aggradation, degradation, and avulsion.
Dn	Denudation	The process by which a slope is stripped bare of vegetation by the processes of weathering transportation or erosion. Resulting slope is more susceptible to infiltration of water and thus increases the through flow erosion hazard.
F	Fires	Removal of the forest cover by fire in the vicinity of the tracks increases the potential for groundwater recharge by: Decreasing evapotransporation, Loss of soil suction Increasing infiltration Increasing potential of blocked, redirected or concentrated drainage (culverts, ditches, bridges), Increasing amount of woody debris. These factors result in a increased potential for railway through flow erosion hazards.
3.Physical Processes		
HW	High Water	Infers high flow rates in rivers which also results in elevated water levels against the slope supporting the track.
HLISM	High level Intense snow melt	Provides rapid release of water for recharge of the regional river system. Rapid melt will result in higher peak flows.
LLISM	Low level Intense snow melt	Provides rapid release of water for recharge of the local streams.
SAR	Significant antecedent rainfall	Provides an abundance of free water for sustained recharge of local streams.
IR	Intense rainfall	Provides a rapid but short duration recharge of the local streams.

Preparatory Causal Factors – Channelized Flow Erosion		Description
4.Man-made or Animal Processes		
LS	Local Scour	Localized deepening of the channel by erosion caused by vortexes created by manmade obstructions such as bridge piers (poor flow attack angles), abutments, rock berms, riprap, or groynes.
GS	General Scour	Localized lowering across a channel due to reduction in the effective width of the channel by manmade constrictions such as rock berms or bridge approach fills, piers and abutments.
BP	Bank Protection	Such as riprap, gabions, anchored logs, groynes
BA	Beaver activity	Beaver habitat in the vicinity of the tracks predisposes the track to the processes of beavers increasing the overland and through flow hazards by: • recent migration of a beaver colony into the watershed (within two months) • a large volume of impoundment in the upper pond as well as two intermediate dams impounding water between the upper dam and the tracks • poor culvert arrangement and location • lack of a buffer or catchment volume upstream of tracks • steep gradient (> 10%) upstream of tracks • denudation of the slopes, • Increasing ground water recharge by dam impoundment, • Increasing potential of blocked, redirected or concentrated drainage causing increased groundwater recharge and impoundment resulting in an increased hydraulic gradient across railway embankments

11.7 Channelized Flow Erosion Hazard Scenarios Trigger Causal Factors

11.7.1.1 Observed Subaqueous Flow Erosion Hazard Scenario Trigger Causal Factors

Table 11-7 presents the trigger causal factors identified for each Subaqueous Flow Erosion Hazard Scenario and for each functional subgroup identified. Table 11-8 provides a summary of the most prevalent trigger causal factors identified for each of the three channelized flow erosion hazard subgroups.

Channelized flow erosion hazard scenarios which can lead to earth slides are predominantly created by the presence or potential for sub-aqueous flow erosion and, in some cases, further erosion during high water flows triggers the slope failure. In many cases the destabilizing removal of material from the toe of slope is offset by the water loading at the toe provided by the high water levels in the river. Then, the earth slide is not triggered until drawdown pore pressure conditions exist in the slope following the water level drop. Depending on the earth soil drainage characteristics of the slope, the author have observed that drawdown conditions are not sufficient to cause failure until the stream is at its low water level months and, in some circumstances, years after the flood event. Given that the slope's stability has been compromised by either toe erosion or the introduction of drawdown pore pressures in the slope, the other prevalent trigger causal factors of intense rain and significant antecedent rain would provide a rapid ingress of water, filling cracks and elevating the pore pressures, triggering an actively unstable slope.

Other obvious trigger causal factors for wave erosion are high winds, tsunamis or boats or ships.

Trigger Causal Factors: CN Western Canada Railway Ground Hazard Scenarios

Level III Subgroups	Ground Hazard Scenario	Coding	Count	Intense Rain	Prolonged Rain	High Water	High Water Table	Piping	Freeze/Thaw	Snow Melt	Raising Freezing Level	Rapid Drawdown	Heavy Snow	Thaw	Anthropogenic	Train Action
Sub aqueous Flow Erosion	**Avulsion Upstream of Tracks**															
	Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow	Av(BH) - DFw / SE / GE / - ESI - EFw -	441	79%	79%	1%	100%	0%	0%	71%	0%	74%	0%	0%	0%	0%
	Erosion /Gully Erosion / Earth Slide - Earth Flow	Av - DFw / SE / GE / - ES - EFw -	28	79%	46%	4%	7%	4%	0%	64%	11%	4%	0%	4%	11%	4%
		Subtotal	**469**	**79%**	**77%**	**1%**	**94%**	**0%**	**0%**	**70%**	**1%**	**70%**	**0%**	**0%**	**1%**	**0%**
	Channelized Flow Erosion Parallel to Tracks															
	Slide	LS / BE - ES -	120	80%	83%	94%	1%	0%	1%	10%	0%	78%	0%	3%	0%	0%
	Bank Erosion - Earth Slide	BE - ESI -	97	95%	95%	100%	5%	0%	0%	9%	0%	96%	0%	2%	0%	0%
	Local Scour / Bank Erosion - Slope wash / Seepage Erosion / Gully Erosion - Earth Slide	LS / BE - SW / SE / GE - ESI -	18	94%	78%	78%	11%	0%	17%	22%	0%	67%	0%	6%	0%	33%
	Bank Erosion / Avulsion Earth Slide	BE / Av ESI	14	71%	64%	64%	0%	0%	0%	7%	7%	57%	0%	0%	0%	0%
	Local Scour / General Scour / Channel Degradation - Earth Slide	LS / GS / ChD - ESI -	7	100%	100%	71%	29%	0%	0%	29%	0%	100%	0%	0%	0%	0%
	Bank Erosion - Rock Slide	BE - RSI -	1	100%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%
		Subtotal	**257**	**87%**	**86%**	**93%**	**4%**	**0%**	**2%**	**11%**	**0%**	**83%**	**0%**	**2%**	**0%**	**2%**
	Channelized Flow Erosion Bridge Crossings															
	Channel Agradation / Debris Flow - Avulsion - Local Scour / Seepage Erosion / Gully Erosion	ChA / DFw - Av - LS / SE / GE -	14	50%	0%	57%	29%	0%	0%	64%	43%	0%	0%	0%	0%	0%
	Local Scour / General Scour / Bank Erosion / Avulsion	LS / GS / BE / Av -	6	50%	33%	100%	0%	0%	0%	17%	0%	17%	0%	0%	0%	0%
	General Scour / ChD - Earth Slide -	GS / ChD - ESI -	2	50%	50%	50%	0%	0%	0%	50%	0%	50%	0%	0%	0%	0%
		Subtotal	**22**	**50%**	**14%**	**68%**	**18%**	**0%**	**0%**	**50%**	**27%**	**9%**	**0%**	**0%**	**0%**	**0%**
	Wave Erosion															
	Wave Erosion - Earth Slide -	WE - ESI -	3	33%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Subtotal	**3**	**33%**	**0%**	**100%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**

Table 11-7 Trigger causal factors identified for each sub-aqueous flow erosion hazard scenario identified. The percentage each trigger causal factor was reported for each hazard scenario and each hazard scenario grouping is

Table 11-8 Summary of prevalent Channelized Flow Erosion hazard trigger causal factors identified according to the functional hazard scenario subgroups.

Sub-aqueous Flow Erosion Hazard Scenario Subgroups	Prevalent Trigger Causal Factors Identified	
Avulsion Upstream of Tracks	• intense rain, • significant antecedent rain • high water • elevated phreatic surface • thaw	• snow melt • rapid drawdown • rain on snow*
Channelized Flow Erosion Parallel to Tracks	• intense rain, • significant antecedent rain	• high water • rapid drawdown
Channelized Flow Erosion Bridge Crossings	• intense rain, • high water	• snow melt • rain on snow*
Wave Erosion	• high water	

* Inferred trigger causal factor given that both intense rain and snow melt are identified

11.7.1.2 Suggested Sub-aqueous Flow Erosion Hazard Event Trigger Causal Factors

The author's suggested list and descriptions of railway channelized flow erosion hazard event trigger causal factors are presented in Table 11-9. In most cases the processes listed in Table 10-11 act as trigger causal factors if they incrementally or rapidly cause the hazard event to occur.

Table 11-9 Suggested railway channelized flow erosion hazard trigger causal factors

Trigger Causal Factors – channelized flow erosion		**Description**
2.Geomorphological Processes		
ChA	Channel Aggradation	As described previously in Section 11.3.1
ChD	Channel Degradation	As described previously in Section 11.3.2
LS	Local Scour	As described previously in Section 11.3.3
GS	General Scour	As described previously in Section 11.3.4
Ij	Ice jams	As described previously in Section 11.3.5
Lj	log jams	As described previously in Section 11.3.6
En	Encroachment	As described previously in Section 11.3.7
BE	Bank Erosion	As described previously in Section 11.3.8
Av	Avulsion	As described previously in Section 11.3.9
LdSl	Landslides (constricting channel)	Landslide constricting the channel upstream, downstream or at the site. Changing sediment supply and promoting aggradation, degradation, and avulsion.
AF	Alluvial Fans	Alluvial fans constricting the channel upstream, downstream or at the site. Changing sediment supply and promoting aggradation, degradation, and avulsion.
Dn	Denudation	The process by which a slope is stripped bare of vegetation by the processes of weathering transportation or erosion. Resulting slope is more susceptible to infiltration of water and thus increases the through flow erosion hazard.
F	Fires	Removal of the forest cover by fire in the vicinity of the tracks increases the potential for groundwater recharge by: • Decreasing evapotransporation, • Loss of soil suction • Increasing infiltration • Increasing potential of blocked, redirected or concentrated drainage (culverts, ditches, bridges), • Increasing amount of woody debris. • These factors result in a increased potential for railway through flow erosion hazards.
3.Physical Processes		
HW	High Water	Infers high flow rates in rivers which also results in elevated water levels against the slope supporting the track.
LLISM	Low level Intense snow melt	Provides rapid release of water for recharge of the local streams.
SAR	Significant antecedent rainfall	Provides an abundance of free water for sustained recharge of local streams.

Trigger Causal Factors – channelized flow erosion		**Description**
IR	Intense rainfall	Provides a rapid but short duration recharge of the local streams.
4.Man-made or Animal Processes		
LS	Local Scour	Localized deepening of the channel by erosion caused by vortexes created by manmade obstructions such as bridge piers, abutments, rock berms, riprap, or groynes.
GS	General Scour	Localized lowering across a channel due to reduction in the effective width of the channel by manmade constrictions such as rock berms or bridge approach fills, piers and abutments.
BP	Bank Protection	Such as riprap, gabions, anchored logs, groynes
BA	Beaver activity	Beaver habitat in the vicinity of the tracks predisposes the track to the trigger causal factor processes of beavers such as: • Recent dam construction • Dam bursts • Recent culvert blockage

11.8 Attributes for Channelized Flow Erosion Scenarios

Table 11-10 provides the author's suggested list of attributes associated with channelized flow erosion scenarios. Included are proposed responses for each of the attributes modified from Porter et al (2005).

Table 11-10 Attributes along with proposed responses for each taken from Porter et al (2005)

Causal Factors	Description	Responses
1. Ground Conditions		
Bed Materials	Based on gradation and genesis	Strong Rock (>R2) Weak Rock (<R2) Dense Till Coarse Colluvium Dense Lacustrine Sediments Coarse Sand and Gravel Alluvium Fine Sand and Gravel Alluvium Soft/Loose Lacustrine Sediments or Loess
Bank Materials	Based on gradation and genesis	Strong Rock (>R2) Weak Rock (<R2) Dense Till Coarse Colluvium Dense Lacustrine Sediments Coarse Sand and Gravel Alluvium Fine Sand and Gravel Alluvium Soft/Sensitive Sediments or Loess
Slope Materials	The natural materials passing beneath the rail grade	Strong Rock (>R2) Weak Rock (<R2) Dense Till Coarse Colluvium Dense Lacustrine Sediments Coarse Sand and Gravel Alluvium Fine Sand and Gravel Alluvium Soft/Sensitive Sediments or Loess
Obstructions	Such as rock knobs, abutments or piers in the floodplain, log jams, beaver dams	Yes No
2. Geomorphologic Processes		
Stream Classification	After Rosgen (1996), incorporating plane form, gradient, entrenchment	Aa+, A, B, C, D, DA, E, F, G
Landslides or Alluvial Fans U/S or D/S	Changing sediment supply and promoting aggradation, degradation, and avulsion	Abundant (affecting >10% of watershed) Few (affecting <10% of watershed) None
Seepage	Evidence of seepage, artesian pressures	Perennial Seasonal None
3. Physical Processes		

Causal Factors	Description	Responses
Angle of Attack	Flow direction relative to the bank (-ve = away from bank; +ve = towards bank)	-90 to +90 deg.
Relative Effective Stream Width	Measure of the channel constriction at bridges, landslides, alluvial fans or other obstructions (influences depth of local and general scour and rate and height of bank erosion)	0.4 to 1.0
Ice Jam Susceptibility	Is this reach of the river prone to ice jamming	Yes No
Potential Woody Debris	Upstream sources, including banks, log jams, beaver dams, and logging	Large Logs Small Debris Little to no Debris
4. Man-made or Animal Activity		
Control Structures	Prevent degradation, such as check dams, lag deposits	Effective Partially effective None
Bank Protection	Such as riprap, gabions, anchored logs, groynes	Effective Partially effective None

11.9 Channelized Flow Erosion Hazard Scenarios Consequence Likelihood Factors

11.9.1 Track Vulnerability

Table 11-11 lists track vulnerability factors corresponding to the mode of track failure and the type of channelized flow erosion hazard.

Table 11-11 Listing of the track failure attributes corresponding to the modes of track failure and channelized flow erosion hazard scenarios.

Modes of Track Failure	**Causative Ground Hazards**	**Track Vulnerability Factors**
Removing support from the track structure;	• Sub-aqueous flow erosion	• Presence and type of retaining structures or bridges • Shoulder width • Presence and type of revetment
Blocking the track;	• Channel aggradation	• Ability for material to pass under tracks (bridges, culverts) • Ditch volume • Particle size, volume and distribution of material blocking track
Damaging track structures (such as bridges, retaining walls or sheds)	• Channelized flow erosion	• Location, shape, orientation, and foundation type of bridge piers and abutments. • Type of retaining wall (Tie-back, cantilever, gravity)

11.9.2 Service Disruption Vulnerability

The service disruption vulnerability factors for channelized flow erosion hazard scenarios given that track failure has occurred include patrols and inspections, presence or absence of warning devices such as tip over posts, train speed, sight lines, grades, site accessibility and traffic frequency. More details on these factors is given in Section 4.6.2.

11.9.3 Derailment Vulnerability

The derailment vulnerability factors for overland / through flow erosion hazard scenarios given that track failure has occurred include patrols and inspections, presence or absence of warning devices, train speed, sight lines, grades, presence or absence of central traffic control circuit in the tracks, site accessibility and traffic frequency. More details on these factors is given in Section 4.6.3.

11.10 Summary

From Chapter 3, although no train accidents were directly attributed to channelized flow erosion events, scenarios initiated by channelized flow erosion, and ultimately caused accidents from either earth landslides or overland / through flow erosion, had a combined frequency of one per year, a severity of $205,000 per accident accounting to

$205,000 per annum occurring mainly on the two main CN corridors in BC which follow main stem rivers.

Channelized flow erosion hazard scenarios are the 2nd most identified hazard scenario group with over 750 sites identified in the hazard database. These hazards fall into a total of 12 channelized flow erosion initiated scenarios which are grouped into four functional subgroups.

470 hazard locations are sub grouped as *avulsion upstream of track* scenarios which contains two scenarios and are predominantly initiated by avulsion caused by beaver activity. The common denominator for these scenarios is the existence of preparatory causal factors that make avulsion, which involves water getting out of its controlled water course (stream bed, ditches, culverts), upstream of the tracks more likely. Thus in Canada, where beaver populations are immense, the activity of beavers create an elevated number of these types of hazard scenarios.

257 are grouped as *channelized flow erosion parallel to tracks* which contains six scenarios and involve mainly locations where the track runs along a main stem river and the track road bed is vulnerable to river attack. The common denominator with these scenarios is that the preparatory causal factors include river processes and river morphology.

22 are grouped as *channelized flow erosion at bridge crossing* scenarios which contains three scenarios and includes sections of track that bridge either main stem rivers or tributary streams and rivers.

There are three *wave erosion* scenario sites identified.

Each of the 11 channelized flow erosion initiated scenarios or FMEA's are described and illustrated by case examples.

In BC where the railways are routed along river valleys, channelized flow erosion, has proven to be a railway ground hazard or a significant component of a number of the ground hazard scenarios identified. Channelized flow erosion depends on the flow velocity, soil characteristics of the channel bottom and bank, vegetation, the channels orientation and proximity to the rail grade and structures and any obstructions to flow including bridges.

Aggradation hazards involving a rise in the stream bottom increase the likelihood of bridge blockage, burial, loading or overtopping; bank erosion; increased flooding; debris blockage or stream avulsion. Degradation hazards involving a lowering of the channel over a reach becomes a hazard if it is likely to undermine a bank slope, or structure supporting the road bed. Causes of degradation include recent glaciation, recent meander cut off, landslide dams, isostatic rebound or tectonic uplift. Local scour is caused by vortexes or preferential erosion created by the outside bend of a meander, differentially erodible material, piers, abutments, bedrock outcrops, boulders, gravel bars, or log jams. General scour hazards involving channel lowering due to a reduction in the effective width are caused by rock berms, bridge approach fills, piers abutments, encroaching alluvial fans, colluvial fans or landslides. Encroachment involves the lateral meandering of a stream which can undermine the rail grade.

Bank erosion hazards involve erosion and landsliding of erodible bank slopes during high water. Eroded slopes are susceptible to rapid draw down conditions.

Avulsion hazards involve water flows not contained in the drainage course resulting from excess flows, blockage, constriction and partial or complete shift of channels. Upstream of tracks intense erosion and subsequent accretion of sediments can potentially blocking culverts or bridges. Beavers cause avulsion hazards as their activity tends to block drainage, increase peak flows and volume, denude the slopes and contribute debris. Beaver dams fail due to deterioration, high water pressures or during torrential rains.

Observed and anticipated rates of track failure from overland / through flow erosion hazards range from slow to rapid depending on the ultimate hazard event before track failure.

The rates reported for system failure from avulsion up stream of tracks hazard scenarios were predominantly rapid due to the speed and volume of the water release; from channelized flow erosion parallel to the tracks were predominantly moderate to slow due to the expected rate of the typical ultimate earth slide event in the scenarios; from channelized flow erosion at bridge crossings ranged from very slow to very fast due to the variety of ultimate hazard events in these scenarios.

Timing within these scenarios are dependent on the return period and magnitude of the initiating rainfall or snow melt event; the flow distance from source to hazard.

Lag time between channelized flow toe erosion and activation of an earth slide can be shortly after triggered by the change in geometry or rapid draw down or after some time following the gradual lowering of the water levels.

Due to the constant presence of channelized erosion processes in close proximity to the tracks these scenarios are typically at a (3) Stable – monitoring required track stability state.

The prevalent recorded preparatory causal factors for avulsions upstream of tracks include beaver activity, susceptibility to rapid draw down, erosion or blockage of culverts, slope or stream erosion, or debris in channels; for river parallel to the tracks include stream erosion, shoulder sloughing, channels prone to shifting, and damaged track structures; and for bridge crossings stream erosion and channels prone to shifting.

Alluvial fan, post glacial landslides, bedrock control and river directional changes causing lateral erosion are the most significant preparatory causal factors which had caused slope instability due to over steepening and undermining in the Fraser Canyon, B.C. (Piteau, 1976).

Suggested preparatory causal factors for channelized flow erosion include:

Ground Conditions:

- Erodible soils
- Dissolution susceptible rock
- Piping susceptible soil
- Dissolution susceptible rock
- Erodible natural materials
- Channel confinement
- Narrow Effective Stream Width
- Large water shed
- Steep gradient
- Plane form geometry
- Relative age

Physical Processes

- High Water
- High level Intense snow melt
- Low level Intense snow melt
- Significant antecedent rainfall
- Intense rainfall

Geomorphological Processes

- Channel Aggradation
- Channel Degradation
- Local Scour
- General Scour
- Ice jams
- log jams
- Encroachment
- Bank Erosion
- Avulsion
- Landslides (constricting channel)
- Alluvial Fans
- Denudation
- Fires

Man-made or animal processes

- Local Scour
- General Scour
- Bank Protection
- Beaver activity

The prevalent recorded trigger causal factors for avulsions upstream of tracks include intense rain and/or snow melt, significant antecedent rain, rapid draw down, and elevated phreatic surface; for rivers parallel to the tracks include intense rain, significant antecedent rain, and rapid draw down; for bridge crossings intense rain, high water and rapid drawdown; and for wave erosion high water.

Suggested trigger causal factors for channelized flow erosion include:

Geomorphological Processes

- Channel Aggradation
- Channel Degradation
- Local Scour
- General Scour
- Ice jams
- log jams
- Encroachment
- Bank Erosion
- Avulsion
- Landslides (constricting channel)
- Alluvial Fans
- Denudation
- Fires

Physical Processes

- High Water
- Low level Intense snow melt
- Significant antecedent rainfall
- Intense rainfall

Man-made or animal processes

- Local Scour
- General Scour
- Bank Protection
- Beaver activity

The author's suggested list of revealing factors and attributes for channelized flow erosion scenarios is listed and includes proposed responses for each. Categories include bed materials, bank materials, slope materials, obstructions, stream classification, natural stream constrictions, seepage, effective stream width, ice jam susceptibility, log jams, control structures and bank protection.

Track vulnerability factors specific to the channelized flow event include presence and type of retaining structures, bridges or revetment; shoulder width; ability for material to pass over or under tracks, ditch catchment, particle size; volume and distribution of material aggrading; location, shape, orientation, and foundation type of bridge piers and abutments.

Service disruption and derailment vulnerability factors include patrols and inspections, presence of warning devices, train speed, sight lines, grades, presence of central traffic control circuit in the tracks, site accessibility and traffic frequency.

Chapter 12 Discussion and Conclusions

12.1 Introduction

This Thesis represents the culmination of 10 years of research by the author to develop and apply a practical and systematic methodology to characterize the full spectrum of railway ground hazards for CN.

Railway ground hazard sites are created by the action of landslides, subsidence, overland flow erosion, through flow erosion, sub-aqueous flow erosion, and/or snow and ice, resulting in unsafe track at the allowable train speed. The risk characterization methodology includes a classification and definition of railway ground hazards, an analysis of the loss using available loss records from CN Western Canada, and systematic identification and characterization of the railway ground hazards from CN Western Canada.

The methodology was developed in accordance with CSA Q850 1997 Risk Management: Guidelines for Decision Makers, and completes the second of six steps in the process, namely Preliminary Analysis. This is the first time this standard has been applied to the risk associated with railway ground hazards. This is also the initial system developed to characterize the full spectrum of railway ground hazards.

The thesis presents:

- A new classification system for railway ground hazards,
- A review and analysis of the CN Western Canada loss records,
- A new risk characterization methodology for railway ground hazard risk scenarios,
- The identification and characterization of railway ground hazard scenarios in CN Western Canada using the methodology and
- The detailed characterization of the identified railway ground hazard scenarios in CN Western Canada in the categories of rock landslides, debris landslides, earth landslides, subsidence, overland/through flow erosion and sub-aqueous flow erosion.

A summary is provided at the end of each chapter. Following is a description and discussion of the significant developments and findings contained in this thesis and conclusions drawn from the Thesis.

12.2 Railway Ground Hazard Classification System

A railway ground hazard classification system is initially developed and presented in Chapter 2 to standardize the identification of railway ground hazard types in Western Canada. The Railway ground hazards are initially grouped into landslides, subsidence, hydraulic erosion and snow and ice hazards. The system uses the established Cruden and Varnes (1996) system to classify landslide hazards, based on their type of material and movement.

Lacking an established classification system for subsidence hazards, a new system is developed, Chapter 2, that first divides the subsidence hazard types into settlement (slow subsidence) and collapse (rapid subsidence). The individual subsidence hazards are classified according to the process causing the subsidence and the controlling material types are indicated in the description of each hazard.

Once again, lacking an established classification system for railway hydraulic erosion hazards, a new system is developed, in Chapter 2, that initially groups railway hydraulic erosion hazards according to the slope hydrologic cycle, into, overland flow, through flow and sub-aqueous flow. The individual hazards are classified according to the predominant process type causing the flow erosion. Due to the high frequency of occurrence and the diversity of river processes, channelized flow erosion hazards are further subdivided according to the predominant channelized flow erosion process expected to cause the hazard event.

The snow avalanche hazard classification is taken from the Canadian Avalanche Association guidelines (CAA, 2002(b)). The icing hazard classification system is new. The railway ground hazard risk characterization system methodology developed in this thesis includes ice and snow hazards however, these hazard sites in CN Western Canada were not characterized using the methodology.

In compliance with CSA Q850-97 and to facilitate a review of the railway loss records, a classification system to measure railway loss is introduced and a correlation is provided to associate these loss types to loss types used in conventional risk management.

Railways measure accidental loss in terms of safety (injury and fatalities), train accidents and cleanup (derailments), train service disruptions and the costs of hazard mitigation.

With only minor changes, the classification system has appropriately captured the full spectrum of ground hazard types identified. As the classification system groups the possible hazard events according to the ground conditions and processes involved, classification provides an immediate understanding or characterization of the mechanics of the individual hazard. It also provides a common glossary of railway ground hazard types for consistent and efficient sharing, collection and understanding of information.

12.3 Analysis of CN Railway Ground Hazard Loss Records

Chapter 3, analysis of CN railway ground hazard loss history, provides a baseline indication of the frequency and severity of loss attributable to railway ground hazards by type of hazard, variations over time and location of occurrence. As a group, ground hazards rank fourth in terms of frequency, first in terms of severity, and third in terms of annual loss against all other railway hazard events that caused train accidents between 1992 and 2002. These results are not surprising when considering that railway ground hazard incidents, by their nature, typically occur in isolated, high relief locations often adjacent to a river, lake or ocean. This setting contributes to incrementally higher severity on average in terms of injury or fatality, property loss, track outages, recovery time and costs, environmental impacts and liability exposures.

A comparison of train accident losses, by individual ground hazard cause, indicates that the highest frequency ground hazard causes are earth landslides (3.2 per year), followed by rock landslides (2.4 per year). The highest severity from ground hazard causes, in terms of the direct cost reported to the Federal Railway Administration (FRA), were through flow hazards ($900,000 per accident), followed by earth landslides ($698,000 per accident). The highest annual FRA reported costs by a large margin were earth landslides ($2,200,000 per year), followed by overland flow erosion ($452,000).

Another significant finding is that 63% of the annual costs from ground hazard events involved more than one ground hazard event acting in sequence or parallel. The term, complex ground hazard, is coined to describe the combination of two or more ground hazard events which can act in series or parallel. This discovery prompted the realization that in order to fully characterize risk scenarios associated with ground hazards, as prescribed by CSA Q850-1997, the methodology would need to map out complex ground hazards from initiating events to track failures. This finding supported the use of failure mode and effect analysis (FMEA) to appropriately model the Railway ground hazard scenarios.

A year to year comparison of frequency, severity and costs of train accident losses due to ground hazards shows that there is considerable fluctuation. This is inferred to be due to the highly variable annual climatic conditions known to have occurred between 1992 and 2002. There is a strong correlation, both regionally and annually, between the higher loss years and significant climate conditions that typically set up during the preceding fall and winter months, such as a high snow pack, deep frost penetration or sustained cold temperatures. As in the case of ground water recharge, frost penetration and accumulation of snow pack, there is a significant time lag before these occasionally extreme climatic conditions result in the occurrence of widespread ground hazard events of a particular type. This lag time represents an opportunity for timely assessment and intervention and thus is included in the characterization methodology.

The Edmonton to Vancouver corridor was found to be the most affected by ground hazards in Western Canada between 1992 and 2002 likely due to the high density of train traffic, the high relief, the close proximity of the track to major rivers, the density and diversity of natural hazards and the relative youth of the river systems.

Rock fall incidents coincide with the mountainous, high-tonnage corridor between Edmonton and Vancouver. Channelized debris flow incidents, coincide with the mountainous terrain along the Edmonton to Vancouver and Tete Jaune to Prince Rupert corridors.

The author infers that earth landslide incidents caused most severe problems along the Edmonton to Vancouver and Tete Jaune to Prince Rupert corridors due to the high relief, the close proximity of the track to major rivers, the youth of the river system, and the abundance of silty and clay soils along these corridors. Earth slide incidents in the Prairie corridors are associated with post-glacial river valleys, particularly where the tracks descend or ascend the valley slopes. Earth slide incidents on corridors that traverse onto the Canadian Shield in Northern Ontario occur most commonly at transitions from weak soils to bedrock due to sloping bedrock surfaces, concentrated seepage paths and weak clay and organic soils.

Settlement caused incidents occur more prevalently in the Interior Plains, presumably due to the abundance of weak clay sub-grades and the lack of drainage in the low relief area.

Overland flow erosion hazard causes are dominated by hazardous beaver activity and thus occur in areas of intense beaver activity in proximity to the tracks, such as in Northern Ontario.

There are only four through flow hazard incidents in the database with the most severe incident occurring in Northern Ontario in a calcareous silt This failure was caused by the propensity of these soils to form cavities.

There were no incidents related directly to channelized flow erosion. However 10 incidents, most of which were along BC rivers, had river erosion as their penultimate hazard event.

The significant reductions in injuries and fatalities associated with rock landslides in BC between 1937 to 1971, and 1972 to present, is attributable to the proactive rock slope mitigation programs started in the 1970's and are testament to the effectiveness of systematic management approaches in reducing the risk associated with ground hazards.

Elaborate ground hazard incident reporting systems like the rock fall reporting system on the CN Yale and Ashcroft Subdivisions, where data has been collected from 1995 to 2003, have shown that they provide valuable quantitative (frequency, volume) and qualitative (characteristics of the event), information essential for risk assessments and ultimately for risk management of these hazards.

12.4 Railway Ground Hazard Risk Characterization Methodology

Current practice at CN for hazards other than rock falls and hazardous beaver activity is reliant on the expertise, experience, memory and judgment of the individual making the assessment. Therefore the decisions made tend to be inconsistent and reactive, as regrettably, there is no historic experience for the decision makers to draw on. The main rationale for using a systematic risk characterization methodology is that only risk relevant engineering information is systematically collected and stored in a database for others to use and build on. As well, the structure of the information is amenable to qualitative and quantitative risk analysis.

Chapter 4 describes a new methodology to systematically characterize all railway ground hazard risk scenarios for use in engineering and risk management. A railway ground hazard risk scenario is comprised of a railway ground hazard scenario, consequences (track failure, service disruption or derailment) and severity of that consequence to the railway. The product of the ground hazard scenario likelihood, the consequence likelihood and the severity is a measure of risk. Thus the characterization methodology is structured according to the risk equation. Information collected using this characterization methodology is intended to facilitate both qualitative and quantitative risk analysis.

The railway ground hazard scenario defined here maps the risk scenario from the initial hazard event through to track failure. More complex ground hazard scenarios can occur both in series, using AND statements, and in parallel, using OR statements, to create more than one likelihood of track failure. This prompted the use of a failure mode and effect analysis (FMEA) method to appropriately map out the fault tree that can lead to track failure. A FMEA selects a failure within a system component (a railway ground hazard event) and then, using a logic tree, projects the effects of this one failure on other system components and on the overall system (Head, 1995). A new method and nomenclature developed here depicts the identified railway ground hazard scenarios through to track failure as a simplified FMEA, and names the FMEA using the glossary of railway ground hazard terms from the classification system. As probabilistic analyses can be completed by assigning estimated probabilities to a FMEA logic tree, this facilitates quantitative risk estimation. This allows comparison not only between hazard sites having the same FMEA but between hazard sites having different FMEA's.

As defined in this thesis, a track failure occurs when the track ceases to be safe for train traffic at the posted track speed. The modes of track failure include removing support from the track structure, blocking the track, striking a train, deflecting the track rail surface, changing the track gauge, damaging the track components or damaging track structures such as bridges or retaining walls. Consequences to the railway are defined in terms of severity of track failure, service disruption or derailment.

The methodology developed to characterize railway ground hazard risk scenarios involves:

- Characterization of the identified railway ground hazard scenarios using failure mode and affect analyses (FMEA).

- Description of the ground conditions and processes associated with each ground hazard event.
- Estimation of the timing, rates and lag time within the railway ground hazard scenarios.
- Identification and description of the preparatory and trigger causal factors associated with each ground hazard type.
- Identification and description of consequence likelihood factors for track failure, service disruption and derailment consequences; and
- Suggestion and presentation of simple and more thorough methods to estimate the potential severity associated primarily with derailment consequences.

The value of identifying and characterizing only the risk scenarios that are known to result in loss is that it limits the required collective experience database to only the information required to evaluate risk. Each of the identified railway ground hazard scenarios have similar conditions and processes; timing, rates and lag time; preparatory and trigger causal factors; and track, service disruption and derailment vulnerability. Therefore once the specific railway ground hazard scenario for a new ground hazard location is identified, the individual can apply all the collective experience associated to that scenario to the new site. In this way the characterization methodology developed and applied in this thesis becomes a valuable tool for systematic education by sharing of experience and understanding of railway ground hazards. If new ground hazard scenarios are identified they can be added to the existing open system.

A new generic subjective criterion is developed to assess track stability states from railway ground hazard activity within a railway ground hazard scenario using identified causal factors. The criterion allows the qualified inspector to assess the site into one of four track stability states, namely:

(1) actively unstable state:

(2) marginally stable state:

(3) stable state – monitoring required:

(4) stable state:

In the past, the four stability states were assessed subjectively. The criteria described in this thesis provide a systematic, repeatable and defensible means to make this critical assessment.

Railway ground hazard causal factors are defined as conditions or processes that either prepare or trigger a railway ground hazard event. Railway ground hazards preparatory causal factors are conditions or processes that make the ground hazard event more likely, without actually initiating it. Preparatory causal factors are useful in the early identification of the ground hazard and in prevention of the ground hazard event by allowing focus on factors that have a significant influence on the potential track failure. Preparatory causal factors are utilized for ground hazard identification, and both qualitative and quantitative risk assessments.

The general requirement for a railway ground hazard trigger causal factor is that it initiates the railway ground hazard event. A trigger for railway ground hazards is defined as an external stimulus or change in preparatory causal factors that causes a near-immediate response in the form of a ground hazard event. Trigger causal factors are utilized primarily for prediction, warning and assessment of the temporal frequency of the events.

The expressions of the causal factors (conditions or processes) at a given ground hazard location are referred to as attributes. Attributes are used as direct and indirect indicators of the existence, extent and nature of an associated causal factor at a hazard site. As well, they are suggested for future use, for calculating component event probabilities within an overall railway ground hazard quantitative risk assessment system. The follow up approach, not completed in this thesis, involves quantifying engineering judgments by developing a set of attributes that provide an indication of probability of hazard occurrence and the probability of system failure, should the hazard occur. Use of quantitative attribute methods to assign event probabilities within a quantitative risk assessment provides an inventory and record of site conditions for tracking changes in conditions over time, a more transparent and repeatable rating process; and a reasonable and defensible estimate of the probability of hazard occurrence or system vulnerability once calibrated using failure statistics, numerical modeling, and engineering judgment. An additional advantage to this approach is that only a select number of relevant factors are collected to complete the risk assessment.

The three main consequence types used by the railways to measure and monitor loss from a railway ground hazard scenario are track failure, service disruption and derailment. Therefore, for the risk formula, the suggested consequence likelihoods are referred to as track, service disruption, and derailment vulnerability. Vulnerability factors are introduced as factors that influence the likelihood that given that the railway ground hazard scenario has occurred, the corresponding consequence occurs. A preliminary listing of the more obvious vulnerability factors are suggested and described for track vulnerability, as well as for service disruption and for derailment vulnerability, independant of track failure mode and ultimate ground hazard event. Assignment of probability values to these factors is left to the risk estimation step, not completed in this thesis. Which of these likelihoods is used in the risk calculation depends on which risk the decision maker is interested in.

The suggested main measures of severity or loss associated with each of the railway consequences include repair costs associated with track failure consequences; net income loss associated with service disruption consequences; and personnel/public loss(safety), repair and cleanup loss, property loss, liability loss, and environmental loss associated with derailment consequences.

The level of effort taken to assess the severity from one of the consequences should be consistent with the purpose of the risk analysis. In most cases the preliminary risk estimation system is set up to manage the number and complexity of particular types of railway ground hazard scenarios and is intended to provide a decision basis for prioritizing monitoring and action requirements for the individual sites. Thus these systems are only required to provide a comparison of risk initially. They only need to be simple, understandable and repeatable to be effective. A simple severity model, as presented in this thesis, is usually all that is required for this purpose. However there may be key sectors or hazards that warrant or lend themselves to a higher level of effort which might include the more complex and robust severity model developed and presented in this thesis.

12.5 Identification and Characterization of Railway Ground Hazards-CN Western Canada

Identification and characterization of the railway ground hazards in CN Western Canada was accomplished through ten years of systematic inspections undertaken by, or under the direct supervision of, the author. Railway ground hazards were initially identified through a review of the loss records; hi rail inspections by either track inspectors or geotechnical engineers; train crew observations; general public observations; helicopter inspections; incident reports; maintenance records; air photo analyses; or by inference.

The geotechnical inspections, excluding rock slope inspections, were completed using a standard geotechnical inspection form developed by the author generally consistent with the Chapter 4 risk characterization methodology. The resulting database represents a comprehensive source of structured railway ground hazard information used in this thesis to risk characterize CN's railway ground hazards in Western Canada. The intent of the form was to identify and characterize the hazard scenario at the site, record the current hazard and site conditions and subjectively assess the action priority and monitoring requirements for the site.

The resulting database contains approximately 1,300 of the most recent records from each non-rock fall hazard site identified. CN's rock fall hazard database containing 1,600 rock fall hazard sites was taken from the CN rockfall hazard and risk assessment (CNRHRA) system, bringing the total number of ground hazard sites in the database to 2,900.

An extensive analysis and review of the database, aided by the author's familiarity with the sites, identified forty railway ground hazard scenarios that described all the identified hazard sites in the database. For further characterization, these forty scenarios are divided into functional subgroups based on the initiating ground hazard event in the scenario. The subgroups include rock landslides, debris landslides, earth landslides, subsidence, overland / through flow erosion, sub-aqueous flow erosion and snow and ice hazard events. Following is a summary of the number of identified hazard sites in each subgroup.

The 1,824 landslide hazard sites are further subdivided into rock landslides containing 1,610 hazard sites, with two scenarios identified; debris landslides containing 44 hazard sites with four scenarios identified; and earth landslides containing 140 hazard sites with six scenarios identified.

The 54 subsidence hazard sites are further subdivided into subgrade plastic deformation containing 20 hazard sites with two scenarios identified; consolidation containing 17 hazard sites with three scenarios identified; compression containing 13 hazard sites with one scenario identified; and subgrade dynamic liquefaction containing 4 hazard sites with two scenarios identified.

Although no ground hazard scenarios were identified with a collapse hazard as an initiating event, these hazards are known to exist and are contained in other scenarios identified.

The 902 hazard sites initiated by hydraulic erosion hazard events are further subdivided into overland/through flow erosion containing 151 hazard sites with six scenarios identified; avulsion upstream of the tracks containing 469 hazard sites, predominantly the result of hazardous beaver activity, with two scenarios identified; channelized flow erosion parallel to the tracks containing 257 hazard sites with six scenarios identified; channelized flow erosion at bridge crossings containing 22 hazard sites with three scenarios identified; and wave erosion containing three hazard sites with one scenario identified.

Snow avalanche and icing hazard sites, in CN Western Canada, were not systematically identified by the author in this database and are thus not characterized in this thesis.

The final section in Chapter 5 describes the structure utilized in the risk characterization of the identified railway ground hazards identified in CN Western Canada in Chapters 6 through 11.

Chapters 6 through 11 apply the risk characterization methodology developed in this thesis to the identified railway ground hazards in CN Western Canada, thereby completing the CSA Q850-1997 Preliminary Analysis step for these hazards. The chapters correspond to the six railway ground hazard scenario subgroups namely rock landslides, debris landslides, earth landslides, subsidence, overland / through flow erosion and sub-aqueous flow erosion. Each chapter is structured according to the characterization system presented in Chapter 4.

The introduction includes a correlation of the frequency and severity of loss associated with scenarios in the sub group with the results of Chapter 3.

The failure modes and effects analysis (FMEA) trees for each scenario in the subgroup are presented and explained, supported in most cases with a case example.

The ground conditions and processes associated with the initiating ground hazard events within the subgroup are identified and described.

The rates, timing and lag time of the railway ground hazard scenario, assessed from the database, or inferred from case examples, are presented and discussed.

The track stability states for the scenarios in the subgroup are discussed using the results of the priority and monitoring assessments completed on the geotechnical inspection forms. A correlation is discussed between the subjective assessments and the new methodologies developed in Chapter 4 to assess the ground hazard activity stage and, by inference, the track stability stage, using the presence or absence of preparatory or trigger causal factors.

The preparatory causal factors associated with the subgroup are identified, described and suggested, using information derived from the database under the categories of erosion, poor drainage, beaver activity, landslide material, landslide movement type and other observations. Also included are suggested summary listings and description of preparatory causal factors developed by the author, subdivided according to the ground conditions and the three process types, namely geomorphological, physical and man or animal made.

The trigger causal factors associated with the subgroup are identified, described and suggested, using information derived from the database. Also included are suggested summary listings and description of trigger causal factors developed by the author, subdivided according to the three process types namely geomorphological, physical and man or animal made.

The consequence likelihood factors for track failure and derailment consequences are suggested for the scenarios in the subgroup.

12.6 Further Work

This thesis sets up the framework for a quantitative attribute approach using FMEA for each of the identified railway ground hazard scenarios and suggests a preliminary glossary and description of ground condition and process causal factors and soil type and landform attributes. This level of effort is all that is required in the preliminary analysis step in the CSA Q850-1997 process. Decisions between steps in the process are represented in the Q850 Model by a decision diamond which has three potential outcomes: End, Go back, or Next step and/or take action. Following are recommendations for advancement of risk management of railway ground hazards to the next steps in the CSA Q850-1997 process.

1. Set up the Risk Library: Continue to develop and populate a relational database, building on the database provided in this thesis which tracks both railway ground hazard incidents and ground hazard locations, from identification to action and monitoring. Integrate the database with an interactive geographic information system.

2. Hazard Identification: Utilize the characterization methodology developed to complete the systematic identification and characterization of railway ground hazard scenarios on all subdivisions. It is recommended that priority be given to scenarios initiated by rock falls from natural slopes, debris flows, earth slide-earth flows in non-cohesive soils, seepage erosion, channelized flow erosion and avulsions upstream of the track.

3. Risk Communicate: Present the findings from this thesis to the engineering functions within the railway and support application of the methodology in the field. This might be accomplished through written guidelines, courses or job aids.

4. Risk Estimation: Utilize the structured information presented in this thesis to advance the more numerous, higher risk scenarios to systematic qualitative and quantitative risk analysis. This involves three steps. First, modify existing systems to allow cross comparison based on risk (I.e. Rock falls (CN RHRA, CPR RHRS) and Avulsion(Beaver Habitat) - Debris Flow / Seepage Erosion /Gully Erosion / Earth Slide - Earth Flow (CN BAHA)). Second, expand these systems to include hazard scenarios initiated by:

    - Rock falls from natural slopes
    - Debris falls

    Third, advance other more numerous, higher risk railway ground hazard scenarios to quantitative risk assessment using the quantitative attribute method described in this thesis. Recommended hazard scenarios are those initiated by:

    - Channelized flow erosion (implement the CN River Attack Track Risk Assessment System (RATRAS))
    - Debris flows
    - Earth slide-earth flows in non-cohesive soils,

    - Seepage erosion
    - Avulsions upstream of the track

5. Risk Evaluation: Communicate the loss record analysis to senior management (decision makers). Use the qualitative and quantitative risk analyses developed for prioritization of monitoring and action.
6. Risk Control: Utilize the structured understanding of the railway ground hazard engineering problem provided here to design and compare risk control options (mitigation, warning, monitoring) and carry out proactive planning and effective crisis management.
7. Action and Monitoring: Implement the risk control measures and assess effectiveness using this system. Monitor identified hazard locations according to the risk analysis and continue to identify and assess new hazards using this system.

In essence, Step 7 completes the loop back to preliminary analysis sustaining the risk management process.

12.7 Conclusions

This thesis completes the requirements of the Preliminary Analysis step of the CSA Q850-97 Standard entitled Risk Management: Guideline for Decision-Makers. The purpose of Preliminary Analysis is to define the basic dimensions of the risk problem and then undertake an analysis and evaluation of risks. The specific tasks completed include:

1. Developing and describing types of ground hazards in the railway ground hazard classification system.
2. Developing and describing loss types associated with railway ground hazard scenarios.
3. Hazard identification through a review of the loss records and ten years of systematic inspections.
4. Identification of railway ground hazard scenarios using FMEA.
5. Development of the structure and initial inputs to the risk information library.

6. Preliminary assignment of frequency and consequence to the risk scenarios.

The preliminary analysis provides sufficient information for the railway risk managers to decide which risk scenarios warrant advancement to the next step of Risk Estimation, and provides the information and structure to make that step.

The railway ground hazard classification system appropriately captures the full spectrum of ground hazard types identified.

Characterization of RGH scenarios into FMEA provides a framework for development of systematic qualitative and quantitative risk analysis where warranted.

The use of FMEA facilitates qualitative and quantitative risk estimation and thus allows comparison, not only between hazard sites having the same FMEA, but between hazard sites having different FMEA.

The thesis divides the engineering and risk problem associated with railway ground hazards into manageable components and identifies the ground conditions and processes that represent the problem parameters.

The thesis facilitates the systematic sharing of the author's experience and understanding of the railway ground hazards in CN Western Canada with CN, other railways, researchers, and other practitioners. It provides an ability for organizations to learn.

Once the appropriate railway ground hazard scenario is identified at a ground hazard site, all the previous engineering experience and understanding associated with that railway ground hazard scenario can be applied to that site. This includes a shortened list of characteristics that are relevant to that hazard to investigate.

The methodology represents a type of expert system that incorporates engineering experience and memory to assess railway ground hazard scenarios.

Information collected and sorted according to this methodology facilitates effective data mining. For instance, if a forecast calls for intense rain in a region, the database could be queried for all hazard scenarios identified in that region susceptible to intense rain trigger causal factors.

As the methodology is flexible and open, and because it identifies and characterizes ground hazard scenarios separate from consequences, it is readily adaptable to other railways and to other consequence systems affected by ground hazards (other linear facilities, mining, forestry or municipalities).

As the classification groups the possible hazard events according to the ground conditions and processes involved, classification provides an immediate understanding or characterization of the mechanics of the individual hazard. It also provides a common glossary of railway ground hazard types for consistent and efficient sharing, collection and understanding of information.

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APPENDIX A

Loss Record Database

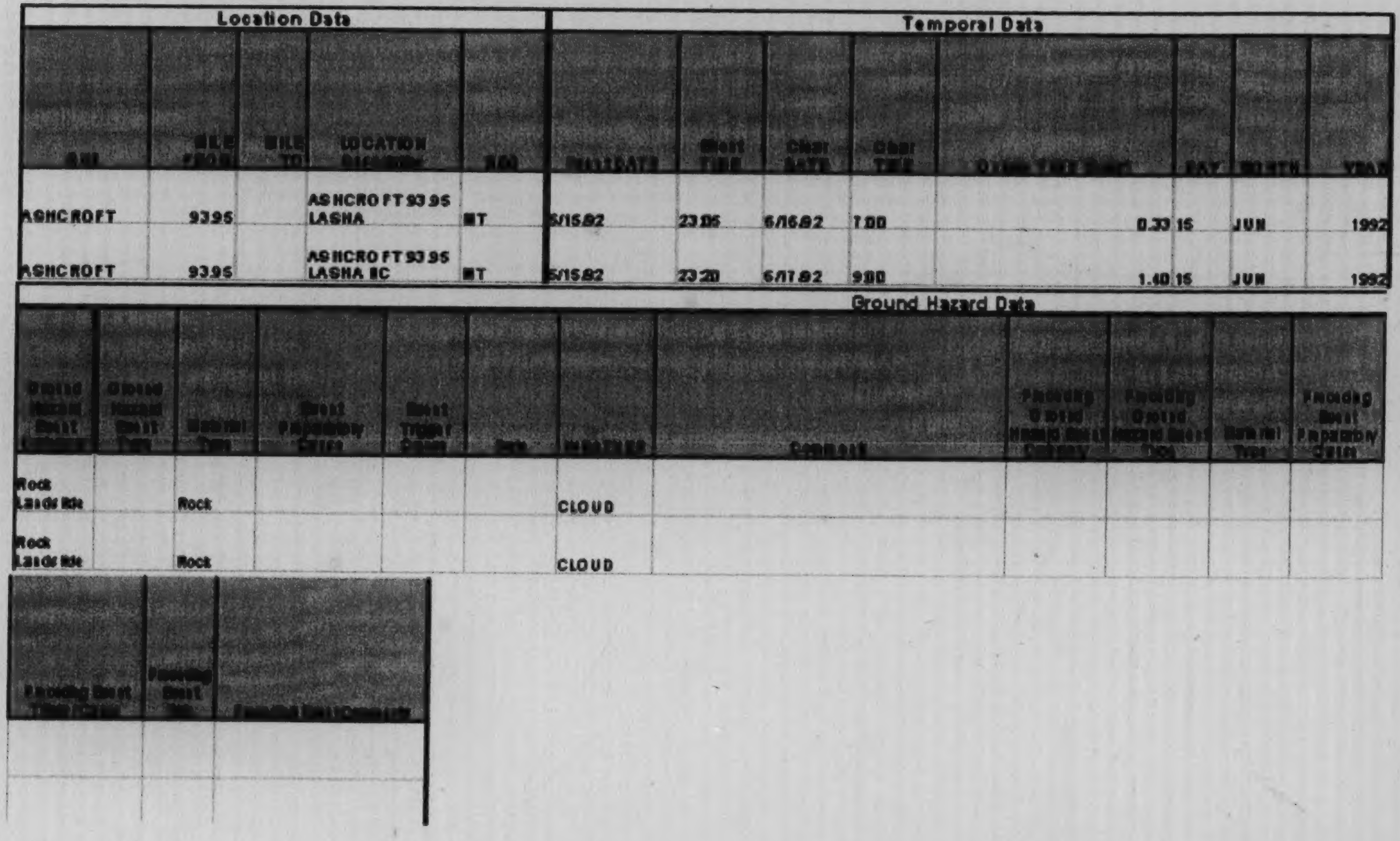
The following Excel© files make up the Loss Record Data Base.

File Name	Size (Mb)	Description
All acid all DIV 92-2001 mainline only.xls	2.3 Mb	Contains records for all mainline train accidents in CN CARES (system wide) from all causes between 1992 and 2002
Ground Hazards-Hazard event Working copy 1992-2003.xls	0.78 Mb	Contains records for all mainline train incidents in CN CARES and major outages in CN Western Canada from ground hazard causes between 1992 and 2003
Ground Hazard casualties 1937 to 1971.xls	0.05 Mb	Summary of injuries and fatalities between 1937 and 1971 on CN and CPR main railway corridors in BC resulting from landslides (from Peckover, 1972)

These electronic files are available only with written permission of the Senior Geotechnical Engineer of CN at the following address (current as of October 2007):

Tom Edwards, P.Eng
Senior Geotechnical Engineer
Canadian National Railway
10229 – 127 Avenue
Walker East Tower, Floor 5
Edmonton, Alberta T5E 0B9
Phone: 780 472 3940
Fax: 780 472 3725
Email: Tom.Edwards@cn.ca

Following are the field headings for the Ground Hazards-Hazard event database 1992 – 2004 CN Western Canada.



Location Data					Temporal Data							
[illegible]	MILE FROM	MILE TO	LOCATION [illegible]	[illegible]	[illegible]	[illegible] TIME	Clear DATE	Clear TIME	[illegible]	DAY	MONTH	YEAR
ASHCROFT	93.95		ASHCROFT 93.95 LASHA	MT	5/15/92	23:05	6/16/92	7:00	0.33	15	JUN	1992
ASHCROFT	93.95		ASHCROFT 93.95 LASHA BC	MT	5/15/92	23:20	6/17/92	9:00	1.40	15	JUN	1992

Ground Hazard Data											
Ground Hazard Event [illegible]	Ground Hazard Event Type	Material Type	Event Preparatory Cause	Event Trigger Cause	[illegible]	[illegible]	Comments	Preceding Ground Hazard Event Category	Preceding Ground Hazard Event Type	Material Type	Preceding Event Preparatory Cause
Rock Landslide		Rock				CLOUD					
Rock Landslide		Rock				CLOUD					

Preceding Event [illegible]	Preceding Event [illegible]	[illegible]

Accident Data						
[illegible] CAUSE CODE	Accident Type	[illegible]	Responsibility and cause DESC [illegible]	UNITS	CARS	CORR ACT
T002	DERAILMENT	EAST. CARS DERAILED AT M. 93.95 AND DRAGGED EAST SWITCH LASHA WHERE TRAIN CAME APART. 6,200 BROKEN CONCRETE TIES, 2 BROKEN RAILS,	ENGINEERING RESPONSIBILITY - ROCK SLIDE AT MP 93.95	0	4	REPAIR SLIDE AREA
T002	DERAILMENT	UP SIGNAL & STRUCK ROCKS FROM ROCK SLIDE. UNIT SUSTAINED MINIMAL DAMAGE, NOTHING DERAILED. FUEL TANK PUNCTURED ON UNIT 5504	ENGINEERING RESPONSIBILITY - ROCK SLIDE AT MP 93.95	2	0	REPAIR SLIDE AREA

Consequence Data						
Health loss (Injuries)	Health loss (Fatalities)	PROPERTY COSTS	TOTAL COSTS	Environmental Loss	Liability Loss	Traffic Level (MGTM)
		390326	401667			
		3000	10240			

Risk Control Data				Data Source	
Mitigation Description	Mitigation Codes	Mitigation Date	Mitigation Costs	SOURCE	FILE
				S&L Records	92137231
				S&L Records	92138600

APPENDIX B

CN Western Canada Railway Ground Hazard Database

The following Excel© workbook, contained on the enclosed CD, make up the CN Western Canada railway ground hazard data base.

File Name	Size (Mb)	Description
Western Canada hazards Sept 27 2006.xls	24 Mb	Contains records for 2790 railway ground hazard identified in CN Western Canada between 1996 and 2005. The main database has 214 fields.

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